Design and simulation of plasmonic metamaterials for sub-wavelength imaging in the visible range

Li, Dongdong

2013

Li, D. (2013). Design and simulation of plasmonic metamaterials for sub-wavelength imaging in the visible range. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/54948>

<https://doi.org/10.32657/10356/54948>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**DESIGN AND SIMULATION OF PLASMONIC
METAMATERIALS FOR SUB-WAVELENGTH
IMAGING IN THE VISIBLE RANGE**

**LI DONGDONG
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
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LI DONGDONG

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

2013

ACKNOWLEDGMENTS

First, I would like to express my heartfelt thanks and appreciation to my supervisor, Professor Zhang Dao Hua, for his precious help, constant guidance, and constructive comments throughout my research work.

I would also express my appreciation to Dr. Yan Changchun for his precious help, support and encouragement on the theoretical research and interpretation of simulation results.

I would like to thank Professor Sir John Pendry (Imperial College, UK), Professor Nikolay Zheludev (Nanyang Technological University, Singapore) and Professor Li Tao (Nanjing University, China) for their valuable advice and comment on the work of dielectric nanorod chain embedded in metal and unidirectional SPPs generator.

Many thanks to our group members: Dr. Bian Haijiao, Dr. Wang Yueke, Dr. Wang Jun, Dr. Yang Xuefeng, Mr. Xu Zhengji, Mr. Jin Yunjiang, Miss Chen Xizi and all the research staff and technician in the Nanophotonics laboratory and Nanyang NanoFabrication Center, for their kind assistance, cooperation and services. It is my great pleasure to know all these fine people during my studies at Nanyang Technological University.

My special thanks go to QianQian, who has been a constant source of unconditional love and support throughout my PhD study.

Last, but not the least, I would also thank Nanyang Technological University for providing me the scholarship and NRF and A-star for the research funding.

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SUMMARY

The resolution of conventional optical lens system is limited by diffraction to about half-wavelength of the incident light. Plasmonic metamaterials, which rely on surface plasmons (SPs) to confine and transmit the electromagnetic (EM) energy, provide a way to circumvent the diffraction-limit. Over the past decades, many plasmonic metamaterial lenses were proposed. However, there are still many issues such as the large material losses and short image transfer distance need to be addressed to realize these lenses. This PhD project numerically investigates several novel plasmonic metamaterial structures and optimizes their performances for sub-wavelength imaging in the visible range. Four kinds of plasmonic metamaterial lenses were investigated. They are the multilayered planar metal-dielectric (MD) structures, the hyperlenses, the dielectric nanorod chain array embedded in the metal and the planar magnifying lens.

The first part of this thesis investigates the imaging performance of the multilayered planar MD structures and the hyperlens. It is found that the imaging performances of them depend on both the super-guiding and transmission properties. A figure of merit (FoM) which accounts both the super-guiding and the transmission was developed to optimize their imaging performance. Numerical simulations showed that the proposed FoM works well for both planar MD structure and hyperlens, and it could be used to optimize the geometric parameters, as well as the working wavelength of such MD structures. The imaging properties of the hyperlens were also examined by a transfer matrix formulation that was developed for evanescent waves in cylindrical coordinate. It is found that the accessible range of the evanescent waves in the hyperlens is larger than that in the planar MD structures, indicating that higher resolution can be achieved by the hyperlens. Furthermore, the imaging properties of a

hemispherical hyperlens for two-dimensional imaging were also investigated. Numerical simulations showed that the hemispherical hyperlens responses to linearly polarized lights regardless of their polarization directions, but only recovers portion of the image along the electrical field direction. In this work, a superposition method by combining the images obtained under different polarization directions was proposed and numerically demonstrated to obtain the complete image.

The second part of the thesis discusses two novel plasmonic metamaterial lenses including the dielectric nanorod chain array embedded in the metal and the planar magnifying lens. The dielectric nanorod chain array embedded in the metal was covered first. Unlike conventional metamaterial lenses that rely on metallic structures as the main transmission medium, the proposed lens uses dielectric as the main medium for image transfer. Numerical simulations revealed that such lenses suppress the coupling among the transmission channels, and transfer the image to a distance comparable to the wavelength. At 560 nm, the proposed dielectric nanorod chain lens demonstrated a resolution of 50 nm. The last section of the thesis discusses a unique planar magnifying lens made of two symmetrically arranged unidirectional surface plasmon polariton (SPP) generators and a multilayered MD structure. Both numerical simulations and theoretical analysis showed that the proposed unidirectional SPPs generator could be used as a scanning probe for high performance imaging. At 533 nm, a resolution of 45 nm and a magnification of 41 were demonstrated. Such a lens has a high potential to be used as a lab-on-chip device for imaging of DNA or virus in a micro-fluid channel.

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Chapter 1. Introduction

1.1 Background and motivation

The resolution of conventional optical lens system is limited by diffraction to about half-wavelength of the incident light [1, 2]. The diffraction-limit arises as results of the missing high spatial information carried by the evanescent waves, leaving only propagating waves in the far-field. Since the invention of the first microscope, the diffraction-limit has mainly been concerned by material and biological scientists [3]. In fact, advances in imaging will not only benefit material and biological research, but also other scientific fields such as data storage, optical communication and nanolithography. Over the past decades, extensive works have been done in searching of sub-wavelength imaging techniques; many sub-wavelength imaging techniques have been proposed [4-15].

One mainstream of research for sub-wavelength imaging is the near-field technique, which seeks to exploit the evanescent waves to overcome the diffraction-limit. Unlike propagating waves, which can be detected in the far-field, evanescent waves are significant only in the near-field of the object due to the exponentially decaying nature. As one of the typical near-field imaging instruments, the scanning near-field optical microscopy (SNOM) uses a nano-sized probe placed close with the object to recover the fine features. However, the SNOM has many drawbacks, such as low speed, low throughput, operation complexity of the scanned data, and inability to capture the image at one scan [16]. The point-by-point scanning nature of SNOM makes it difficult to image dynamic objects such as living cells.

Another sub-wavelength imaging technique, which is also based on detecting the evanescent waves, is the plasmonic metamaterial lens. While evanescent waves may

be picked up with a SNOM probe, it may be well-done with plasmonic nanostructures which support surface plasmons (SPs) with sub-wavelength characteristic wavelength. Such plasmonic metamaterial lenses overcome the diffraction-limit by converting the evanescent waves into SPs. Plasmonic metamaterial lenses use a projection-imaging scheme akin to that of a standard lens, and they provide a convenient way for dynamic imaging.

Over the years, plasmonic metamaterials have drawn great attentions. Several plasmonic metamaterial lenses were proposed; these include the superlenses [9, 17-19], the multilayered metal-dielectric (MD) structures (including the hyperlens) [20-26], the metallic nanowire array structure [27-32], and the metallic nanoparticle chain array structure [33-36]. Some examples of them are illustrated in **Figure 1.1**.

Figure 1.1 Example of plasmonic metamaterial lenses. (a) superlens, (b) hyperlens, (c) metallic nanowire array structure and (d) metallic nanoparticle chain array structure.

These plasmonic metamaterial lenses showed the potential of using engineered nanostructures for sub-wavelength imaging. However, there are still many issues that need to be addressed to realize these lenses practically. For example, their performances are hindered by the large material losses, and the working spectra are relatively narrow and transmission distances are very limited [9, 10, 27, 30]. Although these lenses provide sub-wavelength resolution, it is still a challenge to integrate them with the conventional optical systems. More importantly, most of the previous metamaterial lenses used metal as the main medium for image transfer. New designs should be explored in order to overcome the material losses in metal. In this thesis, the author designed and investigated several novel plasmonic metamaterials lenses and optimized their performances for sub-wavelength imaging. Before discussing these lenses, as background knowledge, it is desirable to have a brief review on metamaterials and plasmonics.

1.1.1 History of metamaterials

Metamaterials have drawn much attention for their intriguing EM properties that are unattainable in natural materials. The emergence of the research on metamaterials brings entirely new prospects in controlling the EM waves. Metamaterials offer great opportunities for several groundbreaking applications, including sub-wavelength imaging [7], optical circuits and antennas [37], nano-scale waveguide [38, 39], chemical/biomedical sensing [40-42], and cloaking [43-45]. As one of the most rapidly developing fields, it is hard to see any fundamental factor that may limit the potential of metamaterials for better control of EM waves [46, 47].

Metamaterials, by definition, are groups of artificial materials that possess EM properties that are not found in nature [48, 49]. They gain the extraordinary properties

from the structures rather than the compositions. The field of metamaterial was started by Professor Sir Pendry who proposed the concept of artificial magnetism [50]. He theoretically proposed the split-ring-resonator (SRR) structure, which extended the permeability to negative regime, and predicted that double negative materials (hence negative refractive index) can be realized by engineered structures [50, 51]. As one of the most fascinating properties of metamaterials, negative refraction has drawn a significant amount of interest due to its potential in nano-focusing and sub-wavelength imaging. Investigations on negative refraction can be traced back to 1967 when the Russian scientist Veselago published his theoretical study on left-handed-materials (LHM). His work predicted many exotic EM phenomena such as negative refraction, reversed Doppler effect and inverse Cherenkov radiation exhibited by LHM materials [52]. These theoretical works on metamaterials completely altered the conventional view on wave-matter interaction. Researchers from different disciplines started to explore the intriguing properties of metamaterials. A remarkable breakthrough was made on the year of 2000, when Smith and his co-workers experimentally demonstrated simultaneously negative permeability (μ) and permittivity (ϵ) in microwave frequencies [53]. Almost at the same time, negative refraction was also observed by Shelby et al. in a wedge shaped structure [54]. As the active elements that used to realize negative permittivity and permeability rely on the development of nanofabrication technologies, most of the early stage research on negative refraction was carried out in microwave frequencies. Although negative permittivity can be obtained in metals in optical frequencies, it is very challenging to design a magnetically active element exhibiting negative permeability in terahertz (THz) and higher frequencies. The advancement of nanofabrication technologies in recent years has greatly accelerated the development of metamaterials. Several groups have

demonstrated negative permeability operating at THz and even at optical frequencies [55-57]. Besides the negative index materials, many other exciting metamaterials were also demonstrated, ranging from microwave frequencies to optical frequencies [40, 58, 59].

With the possible and numerous applications of metamaterials, the optics community quickly adopted the idea. In the optical frequency, metamaterials are essentially plasmonic-like (the permittivities of noble metals are negative in the optical range), and the combination of plasmonic and metamaterials offers more opportunities to tailor the optical properties. Plasmonics or nanoplasmonics refers to the study of optical phenomena related to the EM response of metals in optical or near infrared (IR) regime. This research field is primarily concerned with the manipulation and control of optical radiation in the sub-wavelength scale through excitation of surface plasmons (SPs). SPs usually refer to the collective oscillation of density electron waves bounded at MD interface. SPs are generally classified into two types: surface plasmon polaritons (SPPs) as the propagating modes which exist on the extended interface of metal and dielectric, and localized surface plasmons (LSPs) which exist on small metal particles. Unlike conventional optics, SPs are characterized by their extremely short wavelength and strong field enhancement capabilities [60, 61]. Due to the advantages to confine EM waves in a sub-wavelength scale, both SPPs and LSPs have found wide applications. Many exciting phenomena, such as amplification of evanescent waves, extraordinary transmission, slow light and beam manipulation, can be realized by harnessing the power of SPs [62-65]. These unique features of SPs make plasmonics as one of the potential technologies to create nano-scale photonic devices such as sub-wavelength waveguides, lenses, nanolasers, nanoantennas and sensors. Due to the low-dimensional characteristic of SPs, they may serve as the bridge between the nano-scale

electronic components and the micro-scale photonic devices. It might be possible to realize all-optical circuitry by exploring the full potential of SPs. In this context, SPs become the most promising technology for the next generation chip-level technology. The potential of SPs can be greatly enhanced by incorporating metamaterial concept into its design, which establishes the principles for focusing and manipulating of the light with unprecedented control. This kind of metamaterials in which the functionalities are obtained by harnessing properties of SPs is termed plasmonic metamaterials [66, 67]. Although plasmonic metamaterials is a relatively new term in the scientific world, in fact, people started using such materials several centuries ago. A famous example is the Lycurgus cup made of soda lime glass containing silver and gold nanoparticles. As illustrated in **Figure 1.2**, the cup shows a greenish color under ambient lighting, while a reddish color when it is illuminated from the inside. This fascinating phenomenon is resulted from the LSPs response of the gold and silver nanoparticles in different sizes [68, 69]. The scattering process dominates the extinctions of large nanoparticles, and they scatter predominantly the green light; hence they render a greenish color. While for these small nanoparticles, the extinctions are dominated by absorption of the green and blue light, and they render a reddish color.

Figure 1.2 The Lycurgus Cup (British Museum: AD fourth century). It shows a green color under ambient lighting (a) but a reddish color when illuminated from the inside (b).

1.1.2 Applications of plasmonic metamaterials for sub-wavelength imaging

Based on how the evanescent waves are guided inside the plasmonic metamaterial lenses, the plasmonic metamaterial lenses are classified into three categories in this work. The first category is the layered MD lenses, which includes the superlens and the multilayered MD structures, as illustrated in **Figures 1.1 (a) and (b)**. In such lenses, the evanescent waves are guided through coupled SPP modes propagating in the direction perpendicular to the MD interfaces. Thanks to the negative refraction inside the metal layers, the beam spreading inside the dielectric layers can be perfectly compensated by the negative refraction in metal layers, thus enable super-guiding of the coupled surface plasmon modes below the diffraction-limit [23]. The second category is the pixel-to-pixel lenses, which include the metallic nanowire array and metallic nanoparticle/nanocavity chains, as illustrated in **Figures 1.1 (c) and (d)**, respectively. In such lenses, the evanescent waves are guided along physical channels formed by the metallic nanowire array or metallic nanoparticle/nanocavity chains. Compared with the layered MD lenses in which the imaging performance is mainly determined by their dispersion relations and transmission properties, the imaging performance of such pixel-to-pixel lenses

strongly depends on their geometric structures. In addition to the above two categories, the author also proposes a novel planar magnifying lens with sub-wavelength resolution.

1.1.2.1 Sub-wavelength imaging with the layered MD lenses

Superlens

The emergence of plasmonic metamaterials promises an entirely new prospect to create miniaturized optical devices. One successful implementation of the plasmonics metamaterial concept is the superlens for sub-wavelength imaging. The superlens is a practical implementation of Pendry's perfect lens [7]. In the perfect lens, evanescent waves efficiently couple with the electronic SPPs ($\epsilon=-1$) and magnetic SPPs ($\mu=-1$) and be enhanced by their resonant nature [7]. For any objects close to the perfect lens, all the wave components including the evanescent waves can be refocused at the image plane because of negative refraction. It could be further proved that for transverse-magnetic (TM) waves, when the quasi-static condition is satisfied [7], amplification of the evanescent waves and negative refraction could be realized even if the thin slab is not double negative. Based on this idea, a thin slab of metal, such as silver, could be used as a near-field imaging lens. Fang and his co-workers first experimentally demonstrated the superlens by using a silver slab in ultraviolet (UV) frequencies [9]. Following the same design methodology, several other groups also reported similar lenses [17, 70-72]. However, restricted by the strict matching condition ($\epsilon_{\text{metal}}=-\epsilon_{\text{dielectric}}$) of the superlens [7], practical use of such lenses is still very limited. Most of the metals and dielectrics are dispersive materials, and the dispersive properties of metals are stronger than dielectrics in visible frequencies. The matching condition of the superlens can only be met at one particular wavelength. In addition, as

the permittivities of metals such as silver and gold have much larger magnitude than that of the available dielectrics, it is only possible to meet the matching condition in the UV or deep UV regime. So far, most of the superlenses are silver-polymer based structures that are designed to work around 365 nm, no progresses have been made in the visible and near-infrared frequencies. For biomedical applications, imaging at optical frequency is more desired, especially for biological research where small living entities may possibly be killed under UV exposure. Moreover, the superlens is designed to work at the SPPs resonance frequency that is associated with a tremendous loss. The strong material absorption also limits the practical use of the superlens.

Multilayered MD structures

To address these issues associated with the superlens, one promising design is the multilayer MD structures. Traditionally, multilayered MD structures have been used for optical filtering [73]. A regained interest of the multilayered MD structures has been created recently due to their potential for sub-wavelength imaging. Compared with the superlens, the multilayered MD structures have many advantages, such as a longer image transfer distance, higher tolerance to material losses, wider working spectrum and flexibility in tuning the working frequency.

Over the past years, many multilayered MD structures with improved performance were reported for sub-wavelength imaging [20-23, 74-76]. Among the multilayered MD structures, one outstanding design is the structure made of curved concentric MD multilayer [25]. Because of the hyperbolic dispersion relation, such kinds of curved MD multilayer are named as hyperlens. However, it should be noted that not only plasmonic materials (e.g. MD multilayer) can be used to build hyperlenses, normal dielectrics based on photonic resonances can also be used to build

hyperlenses with a hyperbolic dispersion relation. The hyperlens geometrically magnify the sub-wavelength information such that its smallest feature is larger than $\lambda/2$, thereby transforming the evanescent waves into propagating waves [25, 26]. This unique feature makes hyperlens as one of the most promising tools for far-field sub-wavelength imaging [21, 77-79]. Despite these achievements, there are still many works need to be done in order to improve the imaging performance of the multilayered MD structures. As the multilayered MD structures are one of the most promising plasmonic metamaterials for practical sub-wavelength imaging applications. In Chapter 3 and 4, the optical properties of the multilayered MD structures and hyperlens are investigated, and their imaging properties are optimized by a figure of merit (FoM) proposed in this project.

1.1.2.2 Sub-wavelength with the pixel-to-pixel lenses

Metallic nanowire array

Beside the layered MD lenses, another important imaging scheme is the pixel-to-pixel lenses with physical transmission channels. One typical example is the lenses constructed by an array of metallic nanowires. A metallic nanowire can serve as a transmission channel for image transfer, with the EM energy confined around the vicinity of the nanowires [27-29]. A two-dimensional array of metallic nanowires can be configured as a pixel-to-pixel imaging lens. Such lenses have shown much longer image transfer distances compared with the multilayered MD structures [27]. However, one major concern with the metallic nanowires lenses is the cross-talk among transmission channels. The coupling of surface plasmon modes causes image spreading, and this decreases the resolution. In fact, some research groups have reported that the guided surface plasmon modes in such lenses propagate in the

dielectric background, instead of the metallic nanowires [27]. One method to reduce the coupling among transmission channel is to divide the nanowires into small segments. In this case, the image is transferred along the nanowire segments with the resonance surface plasmon modes supported by individual segment. Since only the resonance surface plasmon modes of individual segments are excited, the cross-talk among transmission channels can be reduced [27]. However, as the transmission channels are separated by the lossless dielectrics, the excited surface plasmon modes on each transmission channel can still extend several tens of nanometers into the dielectrics. The cross-talk remains a problem in such metallic nanowires lenses.

Metallic nanoparticle/nanocavity chains

Beside the segmented nanowire structure, the metallic nanoparticle chain has also shown great potential for sub-wavelength imaging [61, 84-86]. Such structures showed better confinement compared with the nanowire structure [19, 27-29, 32]. The energy transfer process along the metallic nanoparticle chains has been investigated by several groups [33, 36, 87-91]. It is found that such metallic nanoparticles support LSPs, for closely spaced nanoparticles, the near-field interactions setup coupled surface plasmons modes and lead to coherent energy transfer along the metallic nanoparticle chain. It has also been shown that the complementary part of the metallic nanoparticle structures-the metallic nanocavity structure can also sustain LSPs akin to that of the metallic nanoparticle [61, 92]. The metallic nanocavity structure possesses many extraordinary properties such as strong local field enhancement and strong light-matter interaction [93-97]. It might be possible to construct an imaging system similar to the metallic nanoparticle chain structure, but with unique functionalities. As the transmission channels in such nanocavity chains are separated by lossy metals, the

coupling among the transmission channels should be much smaller than that of their complementary structure. This indicates that higher resolution should be possible with such metallic nanocavity chains. As previously proposed sub-wavelength metamaterial structures primarily rely on metal as the main medium to transfer the image, it is worthy to investigate such a structure, which uses lossless dielectric as the main medium for image transfer. In Chapter 5, the waveguiding properties of such metallic nanocavity chains are investigated in two-dimensional space, and a metamaterial lens made of dielectric nanorod chains embedded in the metal is proposed.

1.1.2.3 Sub-wavelength with a novel planar magnifying lens

For a good imaging system, besides sub-wavelength resolution, magnification is also a key requirement. Most of the previous proposed plasmonic metamaterial lenses with magnification capability either use curved surfaces like the hyperlens or radically arranged transmission channels like the metallic nanowire lens to enlarge the image. For real applications, it is more desirable to have a lens with planar input and output surfaces. Although the nanowire array arranged in radical shape can provide magnification with a planar input surface [27, 98], fabrication of such lenses remains a challenge.

In order to realize a planar magnifying lens, two requirements should be satisfied. First, the lens should be capable of picking up the evanescent waves (emitted from two closely spaced objects) and projecting them away from each other. Second, the lens should also be capable of increasing the interspacing of the evanescent waves obtained from each object in order to provide means of magnification. The second requirement can be easily met by a multilayered MD structure with hyperbolic dispersion relation. To meet the first requirement, a device that can be used as a scanning probe and

capable of controlling the light propagation direction is needed. In this work, a specially designed unidirectional SPPs generator is proposed to realize the desired functionality. As illustrated in **Figure 1.3**, the planar magnifying lens uses two closely spaced unidirectional SPPs generators with opposite beam propagation directions as scanning probes; together with the multilayered planar MD structure, the near-field information collected by each SPPs generator can be magnified to a separation above the diffraction-limit. Such lenses have the potential for imaging of the objects in a fluid channel and may possibly be used to construct a lab-on-chip imaging device. In Chapter 6, a compact unidirectional SPPs generator is proposed and a planar magnifying lens made of such unidirectional SPPs generators, and the multilayered planar MD structure is demonstrated.

Figure 1.3 Illustration of the planar magnifying lens.

1.2 Major contribution of the thesis

Based on the above discussions, it can be seen that the multilayered MD structures (including the hyperlens), dielectric nanorod chain array embedded in metal and planar magnifying lenses are three of the most interesting and promising structures for sub-wavelength imaging. In this thesis, the imaging properties of the above three structures are investigated. Based on the understanding of these structures from fundamental physics, their applications for sub-wavelength imaging were investigated. The major contributions of this thesis are:

1. The imaging properties of the multilayered MD structures were investigated by effective medium theory (EMT) and transfer matrix method (TMM). A FoM was proposed to optimize the imaging performance of multilayered MD structures. The proposed FoM was validated by numerical simulations, and the optimized parameters of the multilayered MD structures were obtained by the proposed FoM.

2. A TMM that works for evanescent waves in cylindrical coordinate was developed to calculate the transmittance of the hyperlens. It was found that the transmittance of the hyperlens differs from that of the multilayered planar MD structures. The accessible range of the evanescent wave of the hyperlens is larger than that of the planar MD structures, and simulations showed that higher resolution can be achieved by the hyperlens. The imaging properties of the hemispherical hyperlens were investigated, and two-dimensional sub-wavelength imaging capability of such hemispherical hyperlens was demonstrated.

3. A plasmonic waveguide made of closely spaced dielectric nanorod chain embedded in the metal was proposed. Energy transfer along such dielectric nanorod chains and its complementary structure (metallic nanorod chains embedded in dielectric) was investigated by employing a nanocircuit model. It is found that forward propagating modes are supported by metallic nanorod chains under longitudinal polarization and by dielectric nanorod chains under transverse direction. Numerical simulations showed that higher transmittance can be achieved by the dielectric nanorod chains embedded in the metal when the thickness of the metal interstitial site is kept small.

4. A pixel-to-pixel plasmonic metamaterial lens constructed by dielectric nanorod chains embedded in the metal was proposed. The proposed lens uses dielectric nanorod chains as the primary medium for image transfer. It is found that

the degree of the coupling among the transmission channels can be efficiently suppressed by creating a strong anisotropic along the transverse and image transfer direction. The proposed metamaterial lens has a higher resolution and a longer image transmission distance, compare to other lenses.

5. A new scheme for unidirectional excitation of SPPs was proposed. The proposed unidirectional SPPs generator has a nanoscale width, and it is the smallest unidirectional SPPs generator to the best of our knowledge. In addition, it also has the advantages of broad working spectrum and arbitrary working incident light angle.

6. A planar magnifying lens was proposed and numerically demonstrated. It is made of two unidirectional SPPs generators and a multilayered planar MD structure. The two SPPs generators serve as a scanning probe while the multilayered planar MD structure provides magnification. At 533 nm, a resolution of 45 nm and a magnification of 41 times were demonstrated.

1.3 Outline of the thesis

This dissertation consists of seven chapters. Chapter 1 is the introductory chapter, which presents the background and motivations of the research. The rest of the thesis is organized as follow:

Chapter 2 covers the theoretical knowledge on sub-wavelength imaging and plasmonics. Applications of SPs for sub-wavelength waveguiding using various schemes are discussed. The dispersion relation and plasma frequencies supported by planar MD structures, metallic nanowires, metallic nanoparticles, and nanocavities are discussed in detail. Based on the waveguiding properties of these structures, three categories of imaging schemes are classified.

Chapter 3 investigates the imaging properties of multilayered planar MD structures. Based on the dispersion relation and transmission properties, the sub-wavelength imaging capabilities of multilayered planar MD structures are evaluated. A figure of merit (FoM), which accounts both the super-guiding and transmitting is proposed to optimize the imaging performance of multilayered planar MD structures.

Chapter 4 investigates the imaging properties of the hyperlens. A TMM, which works for evanescent waves in cylindrical coordinate, is developed to calculate the transmission of the hyperlens. The imaging performance of the hyperlens is evaluated and compared with planar MD structures. Furthermore, a hemispherical hyperlens is demonstrated for two-dimensional imaging and its performance under linearly polarized light with different polarizations is investigated.

Chapter 5 covers the works on metallic/dielectric nanorod chains for waveguiding and sub-wavelength imaging. First, the waveguiding properties of such metallic/dielectric nanorod chains under different polarization directions are evaluated, and a nanocircuit model is employed to investigate the energy transfer processes in such structure. Followed by that, the working principle of the lens made of the dielectric nanorod chains embedded in the metal is discussed and its imaging performances is evaluated numerically.

Chapter 6 discusses unidirectional excitation of SPPs and its configuration as a planar magnifying lens with sub-wavelength resolution. This chapter starts with a theoretical investigation of a compact unidirectional SPPs generator, which is used as a probe for sub-wavelength imaging. The performance of the unidirectional SPPs generator was numerically evaluated. The rest of this chapter covers the working principle of the planar magnifying lens. The performance of the planar magnifying lens at different wavelength is assessed.

Chapter 7 concludes the major contributions of this PhD project. This chapter ends by outlooks of the investigated plasmonic metamaterials for other possible applications.

Chapter 2. Theoretical background

This chapter presents the theoretical knowledge on sub-wavelength imaging and the fundamental of plasmonics. A brief discussion on the diffraction-limit and the role of evanescent waves for sub-wavelength imaging is covered first, and then theoretical knowledge of various plasmonic structures for waveguiding is discussed.

2.1 The role of evanescent waves in sub-wavelength imaging

2.1.1. The diffraction-limit

The resolving power of conventional optical system is limited by the diffraction of light [2]. EM waves emitted or reflected from an object consists both propagating and evanescent waves. The fine features are carried by the evanescent waves [14, 18]. The diffraction-limit arises because of the missing high spatial information carried by the exponentially decaying evanescent waves, leaving only propagating waves in the far-field. The nature of the diffraction-limit becomes clear in the Fourier optics when the optical field is decomposed into components with different spatial frequencies [99]. Similar to the concept of 'frequency' and 'time' used in traditional Fourier transform theory, Fourier optics makes use of the spatial frequency domain (k_x, k_y, k_z) as the conjugate of the spatial domain (x, y, z). The spatial frequency is a measure of how often sinusoidal components of the image features repeat per unit of distance, it refers to the periodicity with which the image intensity values change. Image features with high spatial frequency (such as edges and fine features) are those that change greatly in intensity over short image distances. The spatial frequency domain is preferred in imaging analysis, mainly due to two reasons: 1) It directly makes explicit relationships in the spatial domain, and 2) it simplifies the mathematical calculations to make the

image analysis process more efficient. Consider an infinitesimal dipole of frequency ω in front of an ordinary lens where the principal axis of the lens is along y-axis. In Cartesian coordinates, the electric field can be described by the following Fourier expansion

$$E(r, t) = \sum_{k_x, k_z} E(k_x, k_z) \exp(ik_x x + ik_y y + ik_z z - i\omega t) \quad (2.1)$$

For propagating waves, the transverse wave vector $k_t = \sqrt{k_x^2 + k_z^2}$ in x-z plane is smaller than the free space wave vector k_0 . The wave vector along y-axis is positive and can be represented by

$$k_y = \sqrt{k_0^2 - k_x^2 - k_z^2} \quad (k_0^2 > k_x^2 + k_z^2) \quad (2.2)$$

As the EM waves travel away from the source, the amplitude of the propagating waves can be expressed as

$$E(r, t) = \sum_{k_x, k_z} E(k_x, k_z) \exp(i\sqrt{k_0^2 - k_x^2 - k_z^2} \cdot y) \exp(ik_x x + ik_z z - i\omega t) \quad (2.3)$$

For evanescent waves, $k_t > k_0$, and the wave vector along y-axis becomes imaginary

$$k_y = i\sqrt{k_x^2 + k_z^2 - k_0^2} \quad (k_0^2 < k_x^2 + k_z^2) \quad (2.4)$$

As the EM waves travel away from the source, the amplitude of the evanescent waves can be expressed as

$$E(r, t) = \sum_{k_x, k_z} E(k_x, k_z) \exp(-\sqrt{k_x^2 + k_z^2 - k_0^2} \cdot y) \exp(ik_x x + ik_z z - i\omega t) \quad (2.5)$$

Equation 2.5 clearly shows that the magnitude of evanescent waves is modulated by an exponential decaying term. As the evanescent waves travel away from the source, their field strength decreases exponentially. In the far-field, these evanescent waves are completely lost, and only the propagating waves can be retrieved. Ordinary dielectric materials with positive permittivity act like low-pass filters, by which only the spatial

frequencies with transverse wave vector $k_t < k_0$ can be retrieved in the far-field [2]. It can be seen that the evanescent waves play an important role in the imaging process. In order to overcome the diffraction-limit, recovery of the evanescent wave components is essential.

2.1.2 Overcome the diffraction-limit by plasmonic metamaterials

Due to the decaying nature of evanescent waves, they can only be detected in the near-field. One promising near-field imaging method that has drawn much attention is the plasmonic metamaterial lens made of plasmonic materials. From Fourier spectrum analysis, evanescent waves are high spatial frequency components with large transverse wave vectors [100, 101]. To overcome the diffraction-limit, the spatial frequency spectrum response of an optical system should be widened to include the evanescent waves. In plasmonic metamaterials, the evanescent waves can be converted into surface plasmon modes with a characteristic wavelength much smaller than the half-wavelength of the incident light [100]. In Fourier optics, this is equivalent to obtain a dispersion curve with extended accessible range of spatial frequencies. Plasmonic metamaterials allow the coupling and the guiding of the evanescent waves below the diffraction-limit; this is the theoretical basis to use them for sub-wavelength imaging. Since the functionality of such metamaterials is obtained by harnessing properties of plasmonics, it is desirable to have a clear understanding of plasmonics before investigating their applications for sub-wavelength imaging.

2.2 Fundamental of plasmonics

The science of plasmonics is related to the study of the optical phenomena related to the EM response of metals (and some heavily doped semiconductors, too)

[102, 103]. It is mostly concerned with the generation, manipulation and detection of SPPs or LSPs in the sub-wavelength scale. The term "plasmonic" is originated from the fact that metals are plasmas from the EM point of view. They comprise of free-electrons immersed in a background with fixed, positive ion cores. When the free-electrons in metals are excited by an external excitation such as an electron beam, it is possible to obtain a quantized density wave through collective oscillations of the free-electrons. This kind of quantized density wave oscillations in plasma is called plasmon, and the science of engineering the optical properties and functionalities of metal through the manipulation of their plasmon modes is known as plasmonics [60, 104]. The major advantage of plasmonic structures is that they react to evanescent waves and can confine EM energy to volumes much smaller than the incident wavelength. Thus, they have the potentials for sub-wavelength imaging.

2.2.1 Optical properties of metals

2.2.1.1 Drude model

As a starting point to investigate the EM properties of plasmonic metamaterials, the optical properties of metals will be discussed first. The optical properties of metals can be described by a complex dielectric function

$$\varepsilon_m(\omega) = \varepsilon'_m(\omega) + i\varepsilon''_m(\omega) \quad (2.6)$$

where ω is the angular frequency, ε'_m and ε''_m are the real and imaginary parts of the dielectric permittivity, respectively. The EM properties of plasmonics are closely related to the free-electrons (and bounded-electrons in some transition metals) in metals. In the optical frequency, metals are essentially gases of free-electrons moving in a background with fixed, positive ion cores [105]. Over a wide frequency range, the optical properties of metals can be described by Drude's free-electron model with

satisfactory accuracy [106, 107]. Employing the Drude model for free-electron metals, the optical properties of noble metals can be described as a function of frequency [61]

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

where γ is the characteristic collision frequency which accounts the damping due to collisions, ω_p is the bulk plasma frequency of the metal. The bulk plasma frequency is an intrinsic property of metal, and it is related to the free-electron density n and the effective electron mass m_e through the following relation [108]

$$\omega_p = \sqrt{\frac{4\pi ne^2}{m_e}} \quad (2.8)$$

For frequencies close to the bulk plasma frequency, $\gamma\omega$ becomes much smaller than ω^2 , and the imaginary part $i\gamma\omega$ in equation 2.7 can be neglected. The complex permittivity $\varepsilon_m(\omega)$ becomes a real number

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad (2.9)$$

From equation 2.9, it can be seen that the permittivity of a free-electron metal is negative for frequencies below the bulk plasma frequency. This means that the EM waves incident on a free-electron metal induces motion in the charge carriers that act to screen out the incident field (the induced field is 180° out of phase with respect to the incident field). EM waves with the frequency below the bulk plasma frequency cannot penetrate the free-electron metal; instead, they are reflected (as illustrated in the inset "1" of **Figure 2.1**). For frequencies above the plasma frequency, the permittivity becomes positive, and the EM waves can penetrate the sample like most of the transparent dielectric materials, as illustrated in the inset "2" of **Figure 2.1**.

Figure 2.1 Dielectric permittivity $\varepsilon_m(\omega)$ of a Drude free-electron metal with negligible losses.

2.2.1.2 Bulk plasmons in metals

At the bulk plasma frequency ω_p , the permittivity $\varepsilon_m(\omega_p)$ becomes zero. The polarization P induced by an incident field E_{in} becomes

$$P = (\varepsilon_m(\omega_p) - 1) \varepsilon_0 E = -\varepsilon_0 E \quad (2.10)$$

The resulting charge distribution can be interpreted as the eigenmode of the metal. Therefore, the bulk plasma frequency can be recognized as the natural frequency of the oscillating free-electrons in metal. At the bulk plasma frequency, a uniform electrical field (determined by the surface charge density neu) in the metal shifts the oscillating free-electrons with respect to their positive ion cores. The collective oscillations of the free-electrons in a metal at bulk plasma frequency are schematically illustrated in **Figure 2.2**. Analogous to sound waves, such excitations are longitudinal oscillations of free-electron density waves.

Figure 2.2 Bulk plasmons: collective oscillation of free-electron density waves in longitudinal direction.

To distinguish the bulk plasmon from SPPs and LSPs, this kind of plasmons excited in bulk materials are named as bulk plasmons or volume plasmons. Since the free-electron density in noble metals is very high (typically in the order of $10^{23}/\text{cm}^3$), the bulk plasma frequency is high for common metals. The bulk plasma frequencies of some metals are listed in **Table 2.1** [109]. Since the energy required to excite bulk plasmons is much higher than that carried by visible light, bulk plasmons do not couple with visible light.

Metal	$\hbar\omega_p$ (eV)
Ag	9.01
Au	9.03
Cu	10.83
Al	14.98
Cr	10.75
Pt	9.59
Ti	7.29
Pd	9.72
W	13.22

Table 2.1 Bulk plasma frequencies of common metals.

2.2.1.3 Modification of Drude model for real metals

In spite of the fact that the Drude free-electron model revealed several key aspects such as the negative permittivity, it is an over simplified model. It does not account the inter-band transitions (especially in visible frequencies) and the residual

polarization due to the positive background of ions [61]. The residual polarization can be accounted by a dielectric constant ε_∞ , and equation 2.7 becomes

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \quad (2.11)$$

While for the inter-band transitions, more sophisticated models should be developed. The inter-band transitions refer to the excitation of bounded-electrons from the deeper bands into the conduction band, which usually happens in transition metals in visible frequencies [110, 111]. The optical properties of metals have been investigated by several research groups [112-121]. Advanced models such as the Lorentz-Drude model and the Brendel-Bormann model have been developed [122-124]. In addition to these theoretical models, the optical properties of metals can be directly obtained by reflection and transmission measurements such as optical spectroscopy [125]. Many empirical results on the optical properties of metals have also been reported [117, 120, 126]. Some of the widely used optical data of metals are "Optical constants of solids" by Johnson and Christy [117] and "Handbook of Optical Constants of Solids II" by Palik [120]. **Figure 2.3 (a) and (b)** show the permittivities of silver (Ag) and gold (Au) obtained from "Handbook of Optical Constants of Solids II". In the figures, the experimental data (black solid line) are compared with the theoretical model developed by Aleksandar et. al (blue dashed line) [121].

Figure 2.3 Dielectric permittivity of (a) silver and (b) gold.

2.2.1.4 Considerations for the optical data of metallic nanostructures

It should be noted that most of the reported optical data for metals are based on bulk materials, while, for metallic structures with dimensions smaller than the mean free path of free-electrons, the size effects become significant. The size-dependent effects contribute to permittivity from several aspects, which include the quantum size effect [127], the chemical interface effect [128], and the inter-band susceptibility [129]. The first two effects are originated from the increased surface scattering events, which become important in nanostructures with high surface to volume ratio [130, 131]. The modification of the inter-band susceptibility in small structures increases the transition losses. These size-dependent effects increase the imaginary part of the permittivity [132, 133], which usually results in a faster damping of the EM waves in metallic nanostructures. The optical properties of small metallic structures were experimentally measured by many groups [134-139]. However, since all these experimental data are obtained under large ensembles, the collective effects and the inhomogeneous broadening effects may lead to overestimation of the damping due to the surface scattering. In addition, since the size effects depend on the geometry of the nanostructure (such as size and shape) and even the polarization of the incident field, it

is hard to find out the exact experimental data for a particular nanostructure. In this work, the permittivity of the metals is extracted from "Handbook of Optical Constants of Solids II". For simplicity, the effects of the increased damping caused by the small size of the nanostructures are accounted by increasing the imaginary part of the permittivity.

2.2.2 Plasmon modes on planar MD structures

Plasmonics is essentially associated with the investigation on the interplay of electron charges and EM fields. Depending on the external excitations and the boundary conditions, different kinds of charge oscillations (or plasmons) can be excited. In section 2.2.1, it is showed that longitudinal plasmons can be excited in bulk materials. While for the case of MD interfaces and metallic nanostructures, different plasmon modes can be excited. Whereas bulk plasmons do not couple with visible light, MD interfaces and metallic nanostructures can sustain surface plasmon modes via coupling of evanescent waves or other methods to compensate the momentum mismatch. In this section, properties of SPPs on planar MD structures are discussed first.

2.2.2.1. Plasmon modes on a planar MD interfaces

The simplest structure that can sustain SPPs is a single, planar MD interface, in which the excited fields are bounded at the interface with an exponential decaying intensity in the direction perpendicular to the interface. Along the interface, the field intensity and charge distribution in the metal propagates as a longitudinal wave. **Figure 2.4** depicts the electrical field and charge distributions of the SPPs excited at a planar MD interface. The wave vector k_{spp} denotes the wave propagation along the x -

direction. The permittivities of the metal and dielectric are denoted by $\epsilon_m(\omega)$ and $\epsilon_d(\omega)$, respectively. The inset of the figure on the right-hand side illustrates the electric field intensity distribution along the y -direction.

Figure 2.4 Excitation of SPPs at a planar MD interface.

The dispersion relation of SPPs at a planar MD interface can be obtained by solving the Maxwell equations for bounded surface waves. Due to the longitudinal nature of SPPs, they can only be excited by TM waves. Consider the structures illustrated in **Figure 2.4**, for SPPs propagating along the x -direction and homogeneity in the z -direction, the six coupled Maxwell equations

$$\frac{\partial E_z}{\partial y} = -i\omega\mu_0 H_x \quad (2.12a)$$

$$\frac{\partial E_x}{\partial y} - ik_x E_y = i\omega\mu_0 H_z \quad (2.12b)$$

$$ik_x E_z = i\omega\mu_0 H_y \quad (2.12c)$$

$$\frac{\partial H_z}{\partial y} = i\omega\epsilon_0 \epsilon E_x \quad (2.12d)$$

$$\frac{\partial H_x}{\partial y} - ik_x H_y = -i\omega\epsilon_0 \epsilon E_z \quad (2.12e)$$

$$ik_x H_z = -i\omega\epsilon_0 \epsilon E_y \quad (2.12f)$$

reduces to

$$E_x = -i \frac{1}{\omega \epsilon_0 \epsilon} \frac{\partial H_z}{\partial y} \quad (2.13a)$$

$$E_y = -\frac{k_x}{\omega \epsilon_0 \epsilon} H_z \quad (2.13b)$$

for TM incidences, and the wave equation is

$$\frac{\partial^2 H_z}{\partial y^2} + (k_0^2 \epsilon - k_x^2) H_z = 0 \quad (2.14)$$

For bounded surface waves, the following equations should be satisfied

$$H_z(y) = A_d e^{ik_x x} e^{-k_{dy} y} \quad (2.15a)$$

$$E_x(y) = \frac{i A_d k_{dy}}{\omega \epsilon_0 \epsilon_d} e^{ik_x x} e^{-k_{dy} y} \quad (2.15b)$$

$$E_y(y) = -\frac{A_d k_{dy}}{\omega \epsilon_0 \epsilon_d} e^{ik_x x} e^{-k_{dy} y} \quad (2.15c)$$

for $y > 0$ and

$$H_z(y) = A_m e^{ik_x x} e^{k_{my} y} \quad (2.16a)$$

$$E_x(y) = -\frac{i A_m k_{my}}{\omega \epsilon_0 \epsilon_m} e^{ik_x x} e^{k_{my} y} \quad (2.16b)$$

$$E_y(y) = -\frac{A_m k_{my}}{\omega \epsilon_0 \epsilon_m} e^{ik_x x} e^{k_{my} y} \quad (2.16c)$$

for $y < 0$. where A_d and A_m are the magnitude of the magnetic field along the z -direction; k_{dy} and k_{my} are the wave vector components perpendicular to the interface; the subscripts "d" and "m" denote dielectric and metal, respectively. Apply the continuity equations at $y=0$, the following equation can be derived

$$\frac{k_d}{k_m} + \frac{\epsilon_d}{\epsilon_m} = 0 \quad (2.17)$$

Since the wave vectors in the dielectric and the metal also satisfy

$$k_x^2 + k_{dy}^2 = \epsilon_d k_0^2 \quad (2.18a)$$

$$k_x^2 + k_{my}^2 = \varepsilon_m k_0^2 \quad (2.18b)$$

Combination of equations 2.17 and 2.18 give the dispersion relation of SPPs excited at a planar MD interface

$$k_{spp} = k_x = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (2.19)$$

and the wave vectors in the direction perpendicular to the interface are

$$k_{dy} = k_0 \sqrt{\frac{\varepsilon_d^2}{\varepsilon_m + \varepsilon_d}} \quad (2.20a)$$

$$k_{my} = k_0 \sqrt{\frac{\varepsilon_m^2}{\varepsilon_m + \varepsilon_d}} \quad (2.20b)$$

For metals with $Re(\varepsilon_m) < 0$ and $|Re(\varepsilon_m)| > \varepsilon_d$, the wave vector k_{spp} along the interface is real, while the wave vectors k_{dy} and k_{my} perpendicular to the interface are imaginary. This corresponds to surface waves bounded at the MD interface. At the resonance frequency or surface plasma frequency, $Re(\varepsilon_m) = -\varepsilon_d$ and the wave vector k_{spp} approaches infinity (the characteristic wavelength of the SPPs becomes zero). This corresponds to the strong resonance condition of surface plasmon modes. Since the real parts of the permittivities $Re(\varepsilon_m)$ of metals have a magnitude larger than most of the available dielectrics, the surface plasma frequencies usually fall in UV frequencies.

Propagation length and field confinement

The propagation length of the excited SPPs along the MD interface can be estimated by the imaginary part of k_{spp} . For most of the noble metals, $Re(\varepsilon_m) \gg Im(\varepsilon_m)$, and the imaginary part of k_{spp} becomes

$$Im(k_{spp}) \approx k_0 \left(\frac{Re(\varepsilon_m) \varepsilon_d}{Re(\varepsilon_m) + \varepsilon_d} \right)^{\frac{3}{2}} \frac{Im(\varepsilon_m)}{2Re(\varepsilon_m)^2} \quad (2.21)$$

The propagation length is defined as the distance where the intensity decrease to $1/e$, it relates to $Im(k_{spp})$ by

$$L_x = \frac{1}{2Im(k_{spp})} \quad (2.22)$$

For metals such as silver and gold, the propagation length of the SPPs can reach several tens of micrometers in IR and visible frequencies. However, as the incidence frequency getting closer to the surface plasma frequency, the propagation length decreases to a minimum value.

The field confinement in the direction perpendicular to the interface can be evaluated by the penetration depth L_y defined by the imaginary parts of equations 2.20a and 2.20b, which are described by the following equations

$$L_{dy} = \frac{1}{Re(k_{dy})} \quad (2.23)$$

for the dielectric region, and

$$L_{my} = \frac{1}{Re(k_{my})} \quad (2.24)$$

for the metal region. In visible frequencies, the penetration depths in metal and dielectric are typically in the range of ~ 10 nm and ~ 100 nm, respectively. The short penetration depths imply the possibility of using SPPs for guiding of EM wave along the MD interface below the diffraction-limit, which may have potentials for sub-wavelength imaging, nano-scale waveguiding and sensing. Around the SPPs frequency, the penetration depth in both medium approaches zero and the strongest confinement can be achieved at the interface. It can be seen that the propagation length and field confinement of SPPs are inversely correlated. For sub-wavelength imaging, the main issue in this context is to maintain the confinement of the SPPs field in the cross section perpendicular to the MD interface, while keeping the propagation loss low.

SPPs dispersions of a planar MD interface

The dispersion relation of SPPs provides many insights on the optical properties of a planar MD interface. **Figure 2.5** shows the SPPs dispersion relations at the interface between a Drude free-electron metal and different dielectric materials. In the figure, the real parts of the wave vectors are represented by solid curves, while the imaginary parts of the wave vectors are represented by dashed curves. It can be seen that as the frequency approaches the surface plasma frequencies ($\omega_{spp,air}$ and $\omega_{spp,silica}$), the accessible range of the wave vector extended to infinity and the group velocity approaches zero. This is the ideal case when no loss is present. For real metals, the imaginary part of the dielectric permittivity of metal causes damping of the excited SPPs. **Figure 2.6** shows the dispersion relation of SPPs excited at silver/air and silver/silica interfaces with experimental optical data obtained from reference [120]. Compared with the SPPs dispersion relations of Drude free-electron metals, the accessible range of the wave vectors by real metals becomes finite, but still much larger than that of the dielectric. For sub-wavelength imaging, one of the most important parameter is the accessible range of the wave vectors. As the accessible range of SPPs is much larger than that of the dielectric, evanescent waves can couple with SPPs with a characteristic wavelength much smaller than the diffraction-limit, this serves as the basis for the use of SPPs devices for sub-wavelength imaging.

Figure 2.5 Dispersion relations of SPPs at the interface between a Drude free-electron metal and air (blue curves) and silica (black curves). The permittivities of the silica and air are 2.25 and 1, respectively.

Figure 2.6 Dispersion relations of SPPs at the interface between silver and air (black solid curves) and silica (blue dotted curves). (a) Real part of the wave vector versus frequency. (b) Imaginary part of the wave vector versus frequency.

2.2.2.2 Plasmon modes on trilayer MD structures

Similar to the planar MD interface, bounded plasmon modes can be excited on multilayered MD structures. The simplest case is a trilayer system consists of a thin metallic film surrounded by dielectrics, as illustrated in **Figure 2.7 (a)**.

Figure 2.7 Illustration of the SPPs excited on (a) dielectric-metal-dielectric (DMD) structures and (b) metal-dielectric-metal (MDM) structures.

For such dielectric-metal-dielectric (DMD) structures, bounded surface plasmon modes exist on both interfaces. When the thickness of the metal layer is smaller than the penetration depths of the interface modes, the excited SPPs on both interfaces couple with each other and generate coupled SPP modes [140-142]. The coupling results in even and odd eigenmodes of the coupled system with different eigenvalues k_x . For a DMD structure surrounded by same dielectrics as shown in **Figure 2.7 (a)**, its dispersion relation can be evaluated by the following two equations [61, 143, 144]

$$\tanh\left(\frac{1}{2}k_m d\right) = -\frac{\varepsilon_m}{\varepsilon_d} \frac{k_d}{k_m} \quad (2.25)$$

for the even mode, and

$$\tanh\left(\frac{1}{2}k_m d\right) = -\frac{\varepsilon_d}{\varepsilon_m} \frac{k_m}{k_d} \quad (2.26)$$

for the odd mode. The even mode refers to surface plasmon mode with a symmetric distribution of H_z and E_y across the metal layer. Conversely, the odd mode refers to surface plasmon mode with an antisymmetric distribution of H_z and E_y across the metal layer. The wave vectors in metal k_m and dielectric k_d are defined by

$$k_m = \sqrt{k_{spp}^2 - k_0^2 \varepsilon_m} \quad (2.27a)$$

$$k_d = \sqrt{k_{spp}^2 - k_0^2 \varepsilon_d} \quad (2.27b)$$

A plot of the dispersion relation shows that the dispersion curves of the even mode and odd mode converge at the surface plasma frequency $\omega_{spp,air}$ of the metal-air interface, with the same accessible range of the wave vectors. From **Figure 2.8**, it can be seen that due to the splitting of the dispersion curves, large wave vectors k_x are supported even for excitation below the surface plasma frequency $\omega_{spp,air}$. When the thickness of the metal layer is decreased from 50 nm to 30 nm, the degree of the splitting becomes stronger, and larger wave vectors can be accessed at the same frequency. As shown in **Figure 2.8**, at the same frequency, the wave vector (k_{x2}) in the DMD structure with $d=30$ is much larger than k_{x1} in the DMD structure with $d=50$.

Figure 2.8 Dispersion relation of the odd and even SPP modes for DMD structures with metallic layers of 50 nm (short dashed curve) and 30 nm (long dashed curve).

Similarly, for a metal-dielectric-metal (MDM) structure as illustrated in **Figure 2.7 (b)**, the dispersion relations are [61, 145]

$$\tanh\left(\frac{1}{2}k_d d\right) = -\frac{\varepsilon_m}{\varepsilon_d} \frac{k_d}{k_m} \quad (2.28)$$

for even mode, and

$$\tanh\left(\frac{1}{2}k_d d\right) = -\frac{\varepsilon_d}{\varepsilon_m} \frac{k_m}{k_d} \quad (2.29)$$

for odd mode. The dispersion relation of the coupled odd and even modes for a MDM structure is similar to that of the DMD structure.

2.2.2.3 Plasmon modes on multilayered MD structures

The above discussion of coupled SPPs is only limited to three-layer structures. For multilayer MD structures above three layers, more complicated SPPs dispersion curves should be obtained. Due to the coupling of SPPs between adjacent interfaces, the SPPs dispersion curves in multilayered MD structures split into many even and odd modes, similar to that of the energy level splitting in quantum physics. For multilayer MD structure made of an infinite number of MD layers, the SPPs coupling leads to formation of a band-like dispersion relation, similar to that of the energy band in quantum physics. To illustrate the idea, the dispersion relation of a multilayered MD structure made of Ag and SiO₂ is plotted in **Figure 2.9**. The dispersion relation of the multilayered MD structure is obtained by [146]

$$\cos(k_B d) = \cosh(\alpha_1 d_1) \cosh(\alpha_2 d_2) + \frac{\alpha_1^2 \epsilon_2^2 + \alpha_2^2 \epsilon_1^2}{2\alpha_1 \alpha_2 \epsilon_1 \epsilon_2} \sinh(\alpha_1 d_1) \sinh(\alpha_2 d_2) \quad (2.30)$$

$$\alpha_{1,2} = \sqrt{k_{spp}^2 - \left(\frac{\omega}{c}\right)^2 \epsilon_{1,2}} \quad (2.31)$$

where k_B is the Bloch wave number, $d = d_1 + d_2$ (d_1 and d_2 are the thickness of metal and dielectric layers, respectively), ω is the angular frequency, and c is the speed of light in vacuum. From equation 2.30, it is clear that the condition for the existence of propagating Bloch modes is $-1 \leq \cos(k_B d) \leq 1$. As long as the condition $-1 \leq \cos(k_B d) \leq 1$ is satisfied, we can always obtain a dispersion relation by solving equation 2.30. This means that a multilayer MD structure made of an infinite number of MD layers has an infinite number of dispersion curves, which forms a band-like dispersion relation. In the dispersion curve, odd modes have frequencies higher than the respective

frequencies for a single interface SPPs, and the odd modes exist when $-1 \leq \cos(k_B d) < 0$. Even modes have frequencies lower than the respective frequencies for a single interface SPPs, and the even modes exist when $0 < \cos(k_B d) \leq 1$. It can be seen from the figure that the SPPs coupling in multilayered MD structures make it possible to access large wave vectors at frequencies well below the surface plasma frequency, which increases their potential for sub-wavelength applications.

Figure 2.9 SPPs dispersion relation of a multilayered MD structure made of infinite number of alternating Ag and SiO₂ layers. The thicknesses of the Ag and SiO₂ are both 20 nm.

2.2.3 Plasmon modes on metallic nanostructures

2.2.3.1 Plasmon modes on nanowires

While planar MD structures provide one-dimensional field confinement of the plasmon modes perpendicular to the MD interface, two-dimensional field confinement can be achieved on metallic nanowires. Depending on the polarization direction of the incident field, different surface plasmon modes can be excited on a metallic nanowire. For incident light with the electric field E_{Incident} parallel to the principle z -axis of the nanowire, propagating SPPs can be excited along the nanowire. As illustrated in **Figure 2.10**, the excited SPPs on such metallic nanowires propagates along z -axis and provides a two-dimensional confinement. Thus, such metallic nanowire can be

possibly used as waveguiding devices with confinement below the diffraction-limit. Unlike planar MD structures, which rely on phase-matching techniques to excite SPPs, the end of the metallic nanowire can serve as a scattering center and generate the high wave vector components required to excite SPPs. As illustrated in **Figure 2.10 (a)**, the incident field $E_{Incident}$ scatter at the end of the nanowire and generate scattered field $E_{scattered}$ with high transverse wave vector components to excite SPPs on the nanowire.

Figure 2.10 Illustration of the SPPs excited on a cylindrical nanowire. (a) Excitation of SPPs on a cylindrical nanowire. (b) The electrical field strength distribution along the cross section of the nanowire.

The dispersion relation of a metallic nanowire can be derived using the treatment analogous to the DMD structure [147-149], but in cylindrical coordinates. For a metallic nanowire of radius r as shown in **Figure 2.10(a)**, bounded surface modes can be evaluated by solving the following equation [147]

$$k_0^2 \left(\frac{J'_n(k_m r)}{k_m r J_n(k_m r)} - \frac{H_n^{[2]'}(k_d r)}{k_d r H_n^{[2]}(k_d r)} \right) \left(\frac{\epsilon_m J'_n(k_m r)}{k_1 r J_n(k_m r)} - \frac{\epsilon_d H_n^{[2]'}(k_d r)}{k_d r H_n^{[2]}(k_d r)} \right) - n^2 k_z^2 \left(\frac{1}{(k_d r)^2} - \frac{1}{(k_m r)^2} \right)^2 = 0 \quad (2.32)$$

where J_n and $H_n^{[2]}$ are the Bessel function of the first kind and Hankel function of the second kind, respectively. The wave vectors along radial direction k_m (in metal) and k_d (in dielectric) are

$$k_m = \sqrt{\varepsilon_m k_0^2 - k_z^2} \quad (2.33a)$$

$$k_d = \sqrt{\varepsilon_d k_0^2 - k_z^2} \quad (2.33b)$$

Different from the planar MD structures, the number of eigenmodes in cylindrical nanowires is infinite. However, for long straight wires, only the $n=0$ mode is dominant, and equation 2.32 can be simplified to

$$\left(\frac{J'_n(k_m r)}{k_m r J_n(k_m r)} - \frac{H_0^{[2]'}(k_d r)}{k_d r H_0^{[2]}(k_d r)} \right) \left(\frac{\varepsilon_m J'_0(k_m r)}{k_1 r J_0(k_m r)} - \frac{\varepsilon_d H_0^{[2]'}(k_d r)}{k_d r H_0^{[2]}(k_d r)} \right) = 0 \quad (2.34)$$

Since the wave vector k_z along the principle nanowire axis determines the plasmon modes and the surface plasmon frequency, the surface plasmon frequency for a nanowire can be derived by letting $k_z \rightarrow \infty$ in equation 2.34, and it is found that the surface plasmon frequency of a nanowire is the same as that of a planar MD interface.

Figure 2.10 (b) illustrates the field distribution along the cross-sectional of the nanowire, which is very similar to the field distribution in a DMD structure.

2.2.3.2 Plasmon modes on metallic nanoparticles and nanocavities

In previous sections, it is showed that propagating SPPs are supported by both planar MD structures and metallic nanowires. In addition to propagating surface plasmon modes, another important type of surface plasmon mode is the LSPs that are usually associated with metallic nanoparticles and nanocavities. This kind of plasmon modes refer to non-propagating excitations of the free-electrons of metallic nanostructures coupled to an oscillating EM field. Due to the non-propagating nature of the plasmon modes, the EM energy is strongly confined around the metallic nanostructure. Thus, three-dimensional confinement of the EM energy can be achieved by such metallic nanoparticles or nanocavities.

Plasmon modes on metallic nanoparticles

When studying the light-matter interaction of metallic nanostructures, it is of fundamental interest to investigate their polarizabilities, which is a qualitative measurement of the collective electrical response of a nanoparticle to the external EM field. In the quasi-static limit, where the size of a nanostructure is much smaller than the wavelength of external EM field, the polarizability of a metallic nanoparticle can be evaluated by employing the Clausius-Mossotti relation [150]. For the simplest case, the polarizability of an isolated metallic nanosphere with radius a can be described by the following formulation [61, 151]

$$\alpha = 4\pi a^3 \frac{\epsilon_m - \epsilon_d}{\epsilon_m + 2\epsilon_d} \quad (2.35)$$

Equation 2.35 clearly shows that the polarizability of a metallic nanosphere experience a resonance enhancement when the magnitude of its denominator $|\epsilon_d + 2\epsilon_m|$ is a minimum. Strong excitation of LSPs on the metallic nanosphere can be achieved when the Frohlich condition $Re(\epsilon_m) = -2\epsilon_d$ is satisfied. For small nanospheres, the dominated plasmon mode is the dipolar excitation; thus the associated plasmon modes is also called the dipole surface plasmons (or Mie plasmons) [61, 152-154]. **Figure 2.11 (a)** illustrates excitation of dipole plasmon modes in an isolated spherical metallic nanoparticle. For a Drude free-electron metal sphere immersed in a dielectric environment, the resonance condition is satisfied at the frequency

$$\omega_{spp} = \frac{1}{\sqrt{1 + 2\epsilon_d}} \omega_p \quad (2.36)$$

Figure 2.11 Excitation of LSPs on isolated spherical metallic nanoparticles and spherical metallic nanocavities.

Plasmon modes metallic nanocavities

For a metallic nanocavity, which is the complementary structure of a metallic nanoparticle (**Figure 2.11 (b)**), localized collective electron oscillation akin to that of a metallic nanoparticle can be excited on such nanocavities as well. In fact, the polarizability of such a metallic nanocavity can be obtained by exchanging the corresponding permittivities of metal and dielectric in equation 2.35. For a metallic nanocavity in spherical shape, its polarizability is [152]

$$\alpha = 4\pi a^3 \frac{\epsilon_d - \epsilon_m}{\epsilon_d + 2\epsilon_m} \quad (2.37)$$

The Frohlich condition of a spherical metallic nanocavity changed to $Re(\epsilon_m) = -0.5\epsilon_d$. For a Drude metal, the resonance condition of such a spherical metallic nanocavity is met at the frequency

$$\omega_{lsp} = \sqrt{\frac{2}{\epsilon_d + 2}} \omega_p \quad (2.38)$$

One interesting observation obtained from equations 2.36 and 2.38 is that the LSPs resonance frequency of the spherical metallic nanocavity is blue shifted in comparison to the SPPs on planar MD interface, in contrast to red shift for spherical metallic nanoparticles. Although equations 2.35 and 2.37 indicate that both metallic nanoparticles and metallic nanocavity support LSPs, they only showed part of the

picture. The resonance surface plasmons frequency not only depends on the constituent materials but is also affected by the geometric parameters such as the shape and the size of nanostructures [61, 152]. Furthermore, when many of such nanostructures are placed close together, the near-field interaction between them also causes further shifting of the resonance frequency. Compared with the planar MD structure and metallic nanowires, these give the extra degree of freedom in engineering the optical properties of metallic nanoparticles and nanocavities.

Plasmon modes on metallic nanoparticle/nanocavity chains

It can be seen that both the isolated metallic nanoparticle and nanocavity can sustain LSPs at the resonance frequency defined by the Frohlich condition and the particle shape and size. When such structures are arranged to form a one-dimensional array with inter-spacing $d \ll \lambda$, the near-field interactions between adjacent structures can set up coupled plasmon modes and lead to coherent energy transfer along the array [33, 84, 155]. Thus, an array of such metallic nanoparticles and nanocavities could be possibly used as a nanoscale waveguiding device to transfer the energy along the array, analogous to that of a metallic nanowire.

2.2.4 Summary of various plasmonic structures

To conclude, plasmon modes are supported by different metallic structures. Since the light line is located at the right side of the SPs dispersion curves, SPs can only be excited by evanescent waves. The accessible range of the wave vector of a plasmonic device extends to evanescent components, and this forms the basis of using SPs for sub-wavelength imaging. Moreover, the excited SPs can be guided in

dimensions much smaller than the diffraction-limit, which makes it practically possible to construct a lens-like plasmonic device for sub-wavelength imaging.

While planar MD interface provides the one-dimensional confinement of the plasmon modes, two-dimensional confinement of the plasmon modes can be achieved by metallic nanowires, and three-dimensional confinement can be achieved by metallic nanoparticles and nanocavities. At the plasma frequencies, strongest light-matter interaction can be achieved. The dispersion curves of these structures become flat, and the accessible range of wave vectors extends to infinity. **Table 2.2** summarizes the resonance condition of the discussed metallic structures and the corresponding plasmon frequencies.

Metal structures	Resonance condition	Plasmon frequency
Bulk metal	$\varepsilon_m = 0$	ω_p
Planar MD structures	$Re(\varepsilon_m) = -\varepsilon_d$	$\frac{\omega_p}{\sqrt{1 + \varepsilon_d}}$
Metallic nanowire	$Re(\varepsilon_m) = -\varepsilon_d$	$\frac{\omega_p}{\sqrt{1 + \varepsilon_d}}$
Metallic nanosphere	$Re(\varepsilon_m) = -2\varepsilon_d$	$\frac{\omega_p}{\sqrt{1 + 2\varepsilon_d}}$
Metallic nanocavity	$Re(\varepsilon_m) = -0.5\varepsilon_d$	$\frac{\sqrt{2}\omega_p}{\sqrt{2 + \varepsilon_d}}$

Table 2.2 Plasmon frequencies and resonance conditions of bulk metal and metallic nanostructures.

2.3 Summary

In this chapter, the fundamentals of sub-wavelength imaging and plasmonics are discussed in detail. The diffraction-limit arises because of the missing high spatial frequency components carried by the evanescent waves. In the near-field, these evanescent waves can be picked up by plasmonic structures through excitation of surface plasmon modes. Due to the bounded nature of the excited surface plasmon

modes, the evanescent waves can be guided in dimensions much smaller than the incident wavelength. The above two processes form the basis of using plasmonic devices for sub-wavelength imaging.

Chapter 3. Sub-wavelength imaging by multilayered planar MD structures

In this chapter, a FoM is proposed to optimize the imaging performance of the multilayered MD structures. Section 3.1 presents the key requirements for sub-wavelength imaging using multilayered MD structures are discussed in detail. In section 3.2, the imaging capabilities of the multilayered MD structures are analyzed by EMT and TMM. A FoM which accounts both the super-guiding and transmission efficiency is proposed to optimize the imaging performance of the multilayered MD structures.

3.1 Introduction

As one of the most important plasmonic metamaterials, the multilayered MD structures have drawn a lot of attentions due to their various potential applications [21, 155-160]. Under TM polarized illumination, such multilayered MD structures can be engineered to process strong anisotropic optical properties along the longitudinal and transverse directions [20]. As a result, the accessible spatial frequency of such structures can be extended to the evanescent waves. Thus, one of the most important applications of the multilayered MD structures is sub-wavelength imaging. The idea of using multilayered MD structures for sub-wavelength imaging was originally proposed by Ramakrishna and Pendry [161], with an intention to reduce the influence of material losses of the superlens. Compared with the superlens, such multilayered MD structures have many advantages such as broadband response, wavelength tunability, longer image transfer distance and ease of fabrication [20, 161-164]. At visible and

near-infrared frequencies, the multilayered MD structures are one of the most promising plasmonic metamaterials for sub-wavelength imaging.

The imaging properties of the multilayered MD structures have been investigated by many groups [23, 162, 165]. It has been shown that the image transfer in the multilayered MD structures is contributed by two equally important mechanisms, namely transmitting of evanescent waves and super-guiding [23]. From the discussion in chapter 2, it is quite clear that the transmission of evanescent waves in the multilayered MD structures is accomplished by the excitation of coupled SPP modes [7, 23, 161]. Super-guiding refers to the channeling of all the wave components (including the evanescent waves) in the direction perpendicular to the MD interfaces, without any beam spreading. In some other works, the super-guiding is also called self-collimation [166-168]. In the multilayered MD structures, the beam spreading caused by positive refraction in dielectric layers can be perfectly compensated by the negative refraction in metal layers when appropriate geometric parameters and materials are used, thus enable super-guiding [23]. It can be seen that the imaging process in the multilayered MD structures is the interplay of the above two mechanisms, and in order to achieve an optimized performance, both of them should be accounted.

Over the past years, many optimization methods were proposed to improve the imaging performance of the multilayered MD structures. For example, many focused on achieving strong super-guiding by flattening the dispersion relations of the multilayer MD structures [20, 169-171]. Others focused on engineering the transmission properties to obtain higher and smoother transmission curves [24, 165, 172]. Since the imaging performances of the multilayered MD structures depend on both the dispersion relation and transmission, they should not be treated separately. It

is necessary to develop a method as a general guideline to optimize the imaging performance of such structures. In section 3.2, a FoM that accounts both the effect of the dispersion relation and the transmission is developed.

3.2 Imaging properties of the MD structures

3.2.1 Effective parameters of the multilayered MD structures

The optimization and modeling processes are complicated when the multilayered MD structures are treated as discrete metal and dielectric layers. A convenient way to study the optical properties of the multilayered MD structures is to treat them as homogeneous anisotropic mediums. In the quasi-static limit, where the thickness of the individual metal and dielectric layers are much smaller than the incident wavelength, such multilayered MD structures can be approximated as homogeneous mediums [20]. As a convenient tool, the EMT has been widely used in optimizing the imaging performance of multilayered MD structures [20, 165, 169, 171].

Figure 3.1 illustrates a one-dimensional multilayered planar MD structure immersed in vacuum and its effective medium approximation. The permittivity and thickness are denoted by ϵ_m and d_m for the metal layers and ϵ_d and d_d for the dielectric layers, respectively. The effective permittivity tensors of the effective medium along the transverse direction and longitudinal direction are denoted by ϵ_x and ϵ_y , respectively. Based on EMT, when d_m and d_d are much smaller than the wavelength of the incident light, the multilayered MD structure can be approximated as an anisotropic medium with the effective permittivity tensors determined by [20, 161]

$$\epsilon_x = p\epsilon_m + (1-p)\epsilon_d \quad (3.1a)$$

$$\epsilon_y = \frac{\epsilon_m \epsilon_d}{p\epsilon_d + (1-p)\epsilon_m} \quad (3.1b)$$

where p is the filling ratio of the metal, and it is related to the thickness of the metal layers and dielectric layers by

$$p = \frac{d_m}{d_m + d_d} \quad (3.2)$$

Figure 3.1 Effective permittivity tensors of a multilayered planar MD structure.

3.2.2 Dispersion relation and FoM for super-guiding

For nonmagnetic materials ($\mu_r=1$), the dispersion relation of an anisotropic slab (as illustrated in **Figure 3.1**) under TM polarized light is governed by

$$\frac{k_y^2}{|\epsilon_x|} + \frac{k_x^2}{|\epsilon_y|} = k_0^2 \quad (3.3a)$$

with the constraint condition $Re(\epsilon_x)Re(\epsilon_y)>0$, for circular or elliptical dispersion relation [161]. And

$$\frac{k_y^2}{|\epsilon_x|} - \frac{k_x^2}{|\epsilon_y|} = k_0^2 \quad (3.3b)$$

with the constraint condition $Re(\epsilon_x)>0$ and $Re(\epsilon_y)<0$, for hyperbolic dispersion relation.

Where k_0 is the free space wave vector, k_x and k_y are the wave vectors along the transverse and longitudinal directions, respectively. As illustrated in **Figure 3.2**, when the magnitude of the effective permittivity tensors satisfy $|\epsilon_y|>|\epsilon_x|$, the dispersion relations described by equation 3.3 become hyperbola or ellipse with the long axis along the transverse direction. As a result, the accessible range of k_x is extended to the

evanescent waves. At this point, although such anisotropic slabs support evanescent waves, they may not be suitable for imaging. As for imaging purpose, super-guiding should also be satisfied. From the black solid curve in **Figure 3.2 (a) and (b)**, it can be seen that not all the wave components are projected in the direction perpendicular to the output surface. The divergence in wave propagation direction causes beam spreading. In order to achieve super-guiding, the dispersion relation has to be engineered into straight lines, as illustrated by the dotted blue lines in **Figure 3.2**. The desired flat dispersion relation can be realized by creating strong anisotropy with $|\epsilon_y| \rightarrow \infty$ and $|\epsilon_x| \rightarrow 0$. However, in reality, it is never possible to obtain a strictly flat dispersion relation. Due to the presence of material losses, $|\epsilon_y|$ is always finite. A practical way to realize an imaging lens is to obtain a nearly flat dispersion curve by letting $|\epsilon_y| \gg |\epsilon_x|$.

Figure 3.2 Dispersion relations of anisotropic slabs with different anisotropies. Anisotropic slabs with (a) hyperbolic dispersion relations. (b) elliptic dispersion relations. The red arrows denote the energy flow direction. The black solid lines and blue dotted lines denote slabs with weak anisotropy and strong anisotropy, respectively.

The super-guiding capability of the slab can be described by the degree of anisotropy, which can be evaluated by the ratio

$$A = \frac{|\epsilon_y|}{|\epsilon_x|} \quad (3.4)$$

Equation 3.4 can be used as a FoM to evaluate the super-guiding performance of the anisotropic slabs. Numerical simulations by the Radio-Frequency (RF) module of COMSOL Multiphysics 3.5a are carried out to verify the above analysis. In COMSOL, models are built by defining the relevant physical quantities, the software then internally compile a set of partial differential equations (PDEs) representing the entire model. When solving the PDEs, COMSOL Multiphysics uses the finite element method (FEM). The software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers. In the simulations, the effective permittivity along the transverse direction is fixed as $\epsilon_x=1+0.2i$, while the effective permittivity ϵ_y is varied to create different degree of anisotropies. **Figure 3.3** illustrates the schematic of the simulated anisotropic slab with the ambient modeled as vacuum. The thickness of the anisotropic slab is 300 nm. A Chromium (Cr) mask layer with a 30 nm wide slit is used to simulate a sub-wavelength sized object, and a TM polarized ($H//z$ -axis, $\lambda=400$ nm) plane wave is normally illuminated onto it. The permittivity of the Cr is obtained from experimental data [120]. At 400 nm, the permittivity of Cr is $-10.49+10.6i$. The simulation domain has a dimension of 3000 nm $\times$ 3000 nm, with all the boundaries set as perfectly matched layers (PMLs) to reduce the influence of backscattered waves. The maximum mesh size for the Cr layer, anisotropic slab and remaining regions are 0.5 nm, 0.5 nm and 1 nm, respectively.

Figure 3.3 Configuration and geometry of the simulated anisotropic slabs. To show the details of the anisotropic slab, the dimensions of the simulated structure in the figure are not scaled.

The properties of an anisotropic slab with hyperbolic dispersion relation are investigated first. **Figure 3.4** shows the energy flow distribution (or the time averaged Poynting vectors, which accounts both the energy carried by electrical field and magnetic field) inside the slab when the degree of the anisotropy is varied. The effects of $Re(\epsilon_y)$ and $Im(\epsilon_y)$ on the waveguiding properties of the slab are investigated separately. **Figures 3.4 (a)-(d)** show the energy flow distributions when $Re(\epsilon_y)$ is varied to realize different anisotropies of 11.8, 42.5, 83.8 and 166.9, respectively. It is found that the beam spreading decreases as the degree of anisotropy increases. To qualitatively evaluate the energy flow as the anisotropy increases, we measured the full width at half maximum (FWHM) of the beam at the output surface of the slabs. As plotted in Figure 3.5, the corresponding FWHMs in **Figures 3.4 (a)-(d)** are 110 nm, 64 nm, 48 nm and 24 nm, respectively. **Figures 3.4 (e)-(h)** show the energy flow distributions when $Im(\epsilon_y)$ is varied to realize different anisotropies of 11.8, 42.5, 83.8 and 166.9, respectively. The corresponding FWHMs in the figures are 110 nm, 68.5 nm, 62.4 nm and 59 nm, respectively (**Figure 3.5**). From the simulation results, it is clear that the beam spreading in such hyperbolic anisotropic slabs decreases as the degree of anisotropy increases.

Figure 3.4 Waveguiding performance of hyperbolic anisotropic slabs with different anisotropies.

Figure 3.5 FWHM of the beam at the output surface of the hyperbolic anisotropic slabs with different anisotropies.

Next, the waveguiding performance of the elliptic anisotropic slabs with different anisotropies is investigated in a similar way. **Figures 3.6 (a)-(d)** show the energy flow distributions when $Re(\epsilon_y)$ is varied to realize different anisotropies of 11.8, 42.5, 83.8 and 166.9, respectively. As plotted in **Figure 3.7**, the corresponding FWHMs in the figures are 107.6 nm, 107 nm, 80.2 nm and 60.9 nm, respectively. For the figures from **3.6 (e)-(h)**, the corresponding FWHMs in are 107.6 nm, 70.6 nm, 63.6 nm and 60 nm, respectively.

Figure 3.6 Waveguiding performance of elliptic anisotropic slabs with different anisotropies.

Figure 3.7 FWHM of the beam at the output surface of the elliptic anisotropic slabs with different anisotropies.

It can be seen that super-guiding is positively correlated with the degree of anisotropy. Thus, achieving a high degree of anisotropy is essential for sub-wavelength imaging. As discussed in section 3.2, the multilayered MD structure is one of the structures that can be used to achieve strong anisotropy. In the experiments, strong anisotropy can be achieved by optimizing the constituent materials and the thickness of MD layers. For such MD structures, the effective permittivity tensors can be calculated by equations 3.1 and 3.2. Usually, the strength of the anisotropy that can be achieved by real materials is limited, but many materials can be used to achieve an

anisotropy higher than 30 (evaluated by equation 3.4). Many of the numeric simulations in this work showed that good imaging performance can be achieved for MD structures with an isotropy of 20, here an anisotropy of 30 is used as a reference for strong anisotropy. For example, strong anisotropy of 41 and can be realized by Ag and silicon nitride (Si_3N_4) at 400 nm. Many other material combinations such as Ag and titanium oxide (TiO_2), Ag and zinc sulfide (ZnS) also can be used to create strong anisotropic multilayered MD structures. Beside the materials, the degree of anisotropy is also related to the thickness of the MD layers. The thickness of each MD layer has to be controlled with a high degree of precision, and any deviation from the optimized MD layer thickness may decrease the degree of anisotropy. In real experiments, the surface roughness and density of the MD layers also affect the degree of anisotropy that can be achieved. Thus, a sophisticated multilayered thin film fabrication technique is an essential for the fabrication of such MD structures. In this work, a specially designed high vacuum multi-target magnetron-sputtering system is used for the fabrication of high quality thin films. An in-situ ellipsometer is also used to monitor the film thickness in real time.

3.2.3 Transmittance and FoM for the transmittance

The dispersion relation reveals the most information. However, one important feature that it does not cover is the transmittance of the anisotropic slab. As the bandwidth and intensity of the wave components transmitted to the output surface affect the final image quality, the transmittance should also be considered. For an anisotropic slab with a thickness of L , its transmittance for TM polarized light can be expressed by the following equation [20]

$$t(k_x) = \frac{2}{2 \cos(k_y L) - i \left(\frac{k_y}{k_{0,y} \epsilon_x} + \frac{k_{0,y} \epsilon_x}{k_x} \right) \sin(k_x L)} \quad (3.5)$$

where $k_{0,y}$ and k_y are the longitudinal wave vectors in vacuum and the anisotropic slab, respectively. k_y can be evaluated from equation 3.3, and $k_{0,y}$ can be evaluated from

$$k_{0,y} = \sqrt{k_0^2 - k_x^2} \quad (3.6)$$

From equation 3.5, it can be seen that for an anisotropic slab with a fixed thickness L , its transmittance is primarily related to k_y and ϵ_x . For anisotropic slabs with nearly flat dispersion relation, it is easy to show that [165]

$$k_y \approx \sqrt{\epsilon_x} k_0 \quad (3.7)$$

for transverse wave vectors with finite magnitude. Thus, the dependent variables of the transmittance can be reduced into one by replacing k_y by ϵ_x . Although the actual transmittance can be evaluated directly by equation 3.5, it is hard to determine which is better for imaging by barely comparing their transmission curves. A simple FoM used to evaluate the transmittance of an anisotropic medium can be defined by the ratio of the real to imaginary parts of the longitudinal wave vector [173], where the transmittance is

$$|t| \propto \frac{\text{Re}(k_y)}{\text{Im}(k_y)} \quad (3.8)$$

Since it is much easier to know the effective permittivities than the longitudinal wave vector, the FoM in equation 3.8 can be expressed in term of the effective permittivity ϵ_x ,

$$|t| \propto \frac{\text{Re}(\epsilon_x)}{\text{Im}(\epsilon_x)} \quad (3.9)$$

To understand the transmission properties and how the FoM defined in equation 3.9 affects the transmittance, the transmission curves of anisotropic slabs with different ε_x are studied. In the study, $Re(\varepsilon_y)$ is fixed as 1, while $Im(\varepsilon_x)$ is varied to achieve different ratios between $Re(\varepsilon_x)$ and $Im(\varepsilon_x)$. To satisfy the nearly flat hyperbolic dispersion relation for super-guiding, the effective permittivity ε_y is kept as -100 for all calculations. The thickness L of the anisotropic slab and the incident wavelength are assumed to be 300 nm and 400 nm, respectively.

Figure 3.8 shows the transmission curves of the anisotropic slabs when $Im(\varepsilon_x)$ is varied from 0.2 to 0.6. From the figure, two important features can be found. Firstly, the transmittance decreases as the ratio $Re(\varepsilon_x)/Im(\varepsilon_x)$ increases. Secondly, most of the energy that participates in the final imaging process is mainly carried by the wave components with moderate transverse wave vectors, as the contribution of the wave components with extremely large transverse wave vectors are rather small. As illustrated by the dotted cutoff line, for $Im(\varepsilon_x)=0.4$ and $Im(\varepsilon_x)=0.6$, the transverse wave vectors above the cutoff transmission are $k_x < 14k_0$ and $k_x < 9k_0$, respectively. As a very small value ($\log(|t|)=-10$) is considered the cutoff, the actual range of k_x that affects the final imaging quality should be smaller than the one defined by the cutoff transmittance. In fact, it can be seen that all three transmission peaks are located at the region with k_x equals to several times of k_0 (e.g. $k_0 < |k_x| < 4k_0$ for $Im(\varepsilon_x)=0.6$ and $k_0 < |k_x| < 6k_0$ for $Im(\varepsilon_x)=0.4$).

Figure 3.8 Transmission curves of the anisotropic slabs when the imaginary part of the effective permittivity $Im(\epsilon_x)$ along transverse direction is varied. The vertical axis denotes the transmittance $|t|$ in logarithm scale.

To illustrate the phenomenon more clearly, the transmission curve of the anisotropic slab with effective permittivities $\epsilon_x = 1 + 0.4i$ and $\epsilon_y = -100$ is re-plotted in **Figure 3.9 (a)** in linear scale, together with the dispersion relation. It can be seen that the transmittance of the wave components with moderate transverse wave vectors $k_0 < |k_x| < 4k_0$ are much higher than that of the remaining wave components. They carry most of the energy and dominate in the final image formation process. The corresponding dispersion relation of the anisotropic slab is plotted in **Figure 3.9 (b)**. It shows that a nearly flat dispersion can be easily obtained for wave components with moderate transverse wave vectors. Thus, a lossy anisotropic slab can be used as an imaging lens, as long as the dispersion relations of the wave components with moderate transverse wave vectors are nearly flat. This is very necessary for practical imaging since it is never possible to obtain a strict flat dispersion with realistic materials.

Figure 3.9 Transmittance and the dispersion relation of the anisotropic slabs with effective permittivities $\epsilon_x=1+0.4i$ and $\epsilon_y=-100$.

3.2.4 FoM for imaging with a slab of anisotropic medium

Based on the analysis in sections 3.2.2 and 3.2.3, it can be seen that the imaging performances of a lens made of an anisotropic slab are determined by two important factors. Firstly, super-guiding should be satisfied by having a strong anisotropy. Secondly, the transmission of evanescent waves should be maximized by having a low material absorption. Thus, it is possible to define a FoM which takes both the super-guiding and transmission into consideration. The FoM for sub-wavelength imaging with a lens made of the anisotropic mediums can be expressed as

$$FoM = A|t| = \frac{|\epsilon_y| Re(\epsilon_x)}{|\epsilon_x| Im(\epsilon_y)} \quad (3.10)$$

with the constraint condition: $Re(\epsilon_x)Re(\epsilon_y)>0$ for elliptical dispersion relation, and $Re(\epsilon_x)>0$ and $Re(\epsilon_y)<0$ for hyperbolic dispersion relation.

Based on the proposed FoM, the optimized filling ratio of the lens is then evaluated. The effective permittivities of the lens are obtained from realistic multilayered MD structure made of silver (Ag) and dielectric X. The permittivity of Ag is obtained from experimental data [120], while the permittivity of dielectric X is

assumed to be 5 for the spectrum of interest. In optical range, this kind of dielectric material X with a permittivity of 5 can be Titanium dioxide (TiO_2) or Silicon Nitride (Si_3N_4). Assuming a TM polarized incident light with a wavelength of 400 nm, the FoM is used to figure out both the optimized filling ratio p and effective permittivities ϵ_x and ϵ_y . At $\lambda=400$ nm, $\epsilon_{\text{Ag}}=-3.772+0.675i$. The calculated FoM versus the filling ratio p is plotted in **Figure 3.10**. It is found that maximum FoM can be achieved at $p=0.428$, and the optimized effective permittivities are $\epsilon_x=1.2453+0.2888i$ and $\epsilon_y=10.9859+48.3667i$, respectively.

Figure 3.10 FoM versus the filling ratio p . The effective permittivities are obtained from multilayered MD structures made of silver (Ag) and dielectric X.

Numerical simulations are carried out to verify the above theoretical derivation. To maintain consistency, the configurations of simulated lenses are the same as that in **Figure 3.3**. In the simulations, the optimized effective permittivities $\epsilon_x=1.2453+0.2888i$ and $\epsilon_y=10.9859+48.3667i$ are used as the input parameters. **Figure 3.11** shows the energy flow distributions and the point spread function (PSF) of the image measured at the output surface of the lens. To qualitatively evaluate the imaging performance of the lens, the FWHM of the PSF is plotted in **Figure 3.11 (b)**. For the 400 nm incidence, the FWHM of the image is 71.5 nm.

Figure 3.11 Imaging performance of the anisotropic slab with the optimized permittivities. (a) Energy flow distribution inside the slab. (b) PSF of the image measured at the output surface.

The result calculated by the FoM is numerically verified by COMSOL 3.5a. In the simulations, the imaging performance of the lens is evaluated in terms of the maximum intensity and the minimum FWHM of the PSF. **Figure 3.12 (a) and (b)** show the intensity versus the filling ratio, and the FWHM versus the filling ratio, respectively. From the figure, it is seen that the optimized filling ratios evaluated in term of the maximum intensity and minimum FWHM are 0.4 and 0.438, respectively. The optimized filling ratio evaluated by the maximum intensity emphasize more on the transmittance, while that evaluated by the minimum FWHM emphasizes more on the super-guiding. Thus, there is a trade-off between achieving minimum FWHM and maximum intensity. Since the FoM accounts both the transmittance and super-guiding of the slab, a balanced filling ratio $p=0.428$ which is bounded by these two values ($p=0.4$ and $p=0.438$) is found by the proposed FoM. To further verify the above results, the optimized filling ratio at $\lambda=410$ nm is also calculated by the FoM and compared with the numerical results. From the numerical simulations shown in **Figure 3.13**, the optimized filling ratio evaluated in terms of maximum intensity and minimum FWHM from numerical results are 0.42 and 0.505, respectively. The FoM shows that the optimized filling ratio is around 0.468, which is bounded by the two numerical results

($p=0.42$ and $p=0.505$). From the above discussions, it is clear that the proposed FoM accounts both the transmittance and super-guiding of the slab, and a balanced filling ratio can be found by the proposed FoM.

Figure 3.12 Numerical optimization of the filling ratio at $\lambda=400$ nm. The imaging performance of the lenses evaluated in terms of (a) maximum intensity, and (b) FWHM of the PSF.

Figure 3.13 Numerical optimization of the filling ratio at $\lambda=410$ nm. The imaging performance of the lenses evaluated in terms of (a) maximum intensity, and (b) FWHM of the PSF.

Using the same method described in the above paragraph, the optimized filling ratio of the anisotropic slab is numerically evaluated for the wavelength range of 340 nm to 420 nm. **Figure 3.14** shows the optimized filling ratio evaluated in term of maximum intensity and minimum FWHM and the theoretical results calculated by the FoM. As seen from the figure, the optimized filling ratio calculated by the FoM

accounts both the waveguiding and transmittance of the lens. Thus, it can be used as a general rule for optimization of the lenses constructed by anisotropic mediums.

Figure 3.14 Optimized filling ratio of the anisotropic slab evaluated by the FoM and numerical simulations.

The proposed FoM can also be used to determine the optimized working wavelength. Consider a lens made of Ag and dielectric X, the FoM versus wavelength is plotted in **Figure 3.15**. Due to the constraint condition ($Re(\epsilon_x)Re(\epsilon_y) > 0$ for elliptical dispersion relation, and $Re(\epsilon_x) > 0$ and $Re(\epsilon_y) < 0$ for hyperbolic dispersion relation), it is only possible to realize an imaging lens for $\lambda < 425$ nm for the dielectric with a permittivity of 5. The working wavelength can be increased by increasing the permittivity of the dielectric X. From the figure, the highest FoM achieved by the lens is around 163, for the incidence of $\lambda = 400$ nm. The FoM can provide a convenient way to find out the optimized the filling ratio, and the optimized working wavelength of a lens.

Figure 3.15 Optimized working wavelength of the lens made of Ag and dielectric X. The vertical axis denotes the best FoM that can be achieved at the corresponding wavelength.

3.2.5 Considerations for lenses made of practical multilayered MD structures

In this section, the imaging performance of lenses made of practical multilayered MD structures is presented. To investigate how the discreteness affects the imaging performance of the lenses, TMM is used to calculate the transmission curves. The TMM formulation developed in this work has taken into account the dispersion, absorption and thickness of the individual MD layers. In the study, the total thickness of the lens and the incident wavelength are set to 300 nm and 400 nm, respectively. The multilayered MD lens is made of Ag and dielectric X, as used in section 3.2.4. The filling ratio is fixed as 0.428, while the total number of MD pairs is varied. **Figure 3.16** shows the transmission curves of the lenses made of different number of MD pairs. It is seen that, for multilayered MD structures with a sufficient number of MD pairs (e.g. 20 MD pairs), their transmission curves are in excellent agreement with the EMT prediction. However, the transmittance attenuates as the number of MD pairs is decreased. In the effective medium limit, waves with infinite wave vectors are supported. In the practical multilayered MD structures, the finite thickness of the MD layers places an upper cut off to the largest wave vectors that can be transmitted through the lens. The waves with wave vectors comparable to the inverse of the

thickness of the MD layers do not perceive the effective medium limit but suffer Bragg scattering [174]. To improve the transmittance, the individual metal and dielectric layers should be as thin as possible.

To visualize the effect of discreteness in the imaging performance of the multilayered MD lenses, the energy flow distributions inside the lenses made of different number of discrete Ag and dielectric X pairs are compared. As shown in **Figure 3.17 (a)-(d)**, the energy flow distributions approach that of the lens made of homogeneous mediums as the number of the Ag-X pairs increases. A clearer view can be found in **Figure 3.17 (e)** which shows the field intensities along the transmission path in the lenses.

Figure 3.16 Transmission curves of the lenses made of silver and dielectric X pairs and effective homogeneous medium.

Figure 3.17 Effect of the discreteness in the imaging performance of the multilayered Ag-X lenses. (a)-(d) illustrate the energy flow distributions inside the lenses made discrete Ag-X layers and the lens made of effective medium. Figure (e) shows the calculated energy flow inside the lenses.

To verify the validity of the FoM for lenses made of discrete MD layers, the optimized filling ratios of practical lens made of 5-pair, 10-pair and 20-pair of Ag-X layers are simulated for the incidence of 400 nm. The simulation results are tabulated in **Table 3.1**, together with the theoretical calculations. Due to the finite number of layers in the practical lens, the results deviate from that calculated by the FoM and the EMT. It is also found that the optimized filling ratios evaluated in term of the minimum FWHM are quite close to the theoretical value of 0.428 calculated by the FoM, even for a lens made of five pairs of Ag-X layers. This can be explained by the waveguiding mechanism in a practical multilayered MD structures. Since the waveguiding function in such structures is achieved by the perfect balancing of the positive refraction in dielectric layers and negative refraction in metal layers, the decreased number of the MD pairs does not affect the waveguiding properties much. For high-resolution imaging, it is more concerned with the resolving power of the

lenses, and the FoM can be used to find the optimized filling ratio around the minimum FWHM.

	Practical multilayered Ag-X lenses		EMT		FoM
	Min FWHM	Max Intensity	Min FWHM	Max Intensity	
5-pair	$p=0.39$	$p=0.33$	$p=0.438$	$p=0.4$	$p=0.428$
10-pair	$p=0.41$	$p=0.34$			
20-pair	$p=0.41$	$p=0.35$			

Table 3.1 Comparison of the optimized filling ratios obtained by different methods.

The immediate conclusion from this work is that the EMT provides sufficient information to describe the imaging properties of the multilayered MD structures. Although the optimized filling ratio evaluated in term of the maximum intensity deviates from the value calculated by the FoM, the optimized filling ratio evaluated in term of the minimum FWHM fits well with the theoretical value. When it is more concerned with the resolving power of the lens, the proposed FoM can provide a good degree of accuracy in finding the optimized filling ratios.

3.2.6 Limitations of the multilayered planar MD structure for imaging

One major limitation of the multilayered planar MD structure is that they only provide a mean to transfer the image to a further location without magnification. Near-field techniques are still required to recover the image at the output surface of such planar MD structure. Because of this limitation, such multilayered planar MD structures cannot be integrated with conventional optical system for further image processing. In addition, the transmittance of the multilayered planar MD structure is rather low. The energy carried by evanescent waves has to tunneling through the lossy metal layers in order to form an image at the output surface. In practice, only a very small portion of the energy can be transmitted through the structure.

Despite the limitations of the multilayered planar MD structure, it still represents an excellent design to overcome the diffraction-limit with a long image transfer distance. Such kind of lenses may be possibly realized in the future when low-loss metals are available, or by using gain materials to compensate the losses in metal layers.

3.3 Summary

The imaging performance of multilayered planar MD structures is primarily determined by the degree of the anisotropy and transmission properties of the structure. A FoM which accounts for both the super-guiding and transmitting of evanescent waves is proposed to optimize the imaging performance of such multilayered planar MD structures. The numerical results evaluated in terms of minimum FWHM are similar to those calculated by the FoM, but slightly differ from those evaluated in terms of maximum intensity. Since the sub-wavelength imaging is more concerned with the resolving power of the lens, the FoM proposed in this work should be sufficient as a guideline to design such lenses.

Chapter 4. Sub-wavelength imaging by hyperlens

This chapter presents the work on cylindrical hyperlenses. Section 4.1 introduces the background and motivations of the research. In section 4.2, a transfer matrix formulation is developed to calculate the transmittance of the evanescent waves in cylindrical hyperlens. The imaging performance of the hyperlens is optimized by the proposed FoM in the previous chapter. Section 4.3 presents the simulation results on two-dimensional sub-wavelength imaging by a hemispherical hyperlens. The imaging properties of the hemispherical hyperlens under different polarized light were investigated.

4.1 Introduction

The multilayered planar MD structures do not provide magnification. For a good imaging system, it is also desired to have magnification, so that the image can be magnified above the diffraction-limit for further processing by conventional optical system. Magnification can be achieved by multilayered MD structures in cylindrical shapes. Historically, this kind of structures is also called hyperlens because of their hyperbolic dispersion relation [21, 25, 26, 78, 97, 175-180]. However, it should note that not only plasmonic structures such as the MD multilayered can be used to build hyperlenses, normal dielectrics based on photonic resonances can also be used to build hyperlenses with a hyperbolic dispersion relation. Different from the multilayered planar MD structures, the hyperlens mimics the function of a magnifying lens. The hyperlens geometrically magnify the sub-wavelength information such that its smallest feature is larger than $\lambda/2$, thereby transforming the evanescent waves into propagating waves. This unique feature makes hyperlens one of the most promising tools for far-

field sub-wavelength imaging. Over the past years, the cylindrical hyperlenses have been investigated by many groups [21, 77, 176, 179-184]. Many of the previous works used the same optimization methods used for multilayered planar MD structures. However, due to the small radius of the cylindrical hyperlenses, the optical properties of hyperlens may deviate from that of the planar case, especially for the transmission properties. As discussed in Chapter 3, SPP coupling plays an essential role in the energy transfer process in multilayered MD structures. The SPP modes that supported by such multilayered MD structures are determined by the materials and geometries, and it affect the imaging performance including the transmission and resolution. Due to the curved surface and small inner radius (in the scale of incident wavelength), the supported SPP modes by the hyperlens is different from that of the planar case. At the input surface of the hyperlens, the excited SPP modes are essentially restricted in a confined space. The confinement gives rise to localized characteristics of the SPP modes excited at the input surface. In addition, the curved geometry of the hyperlens also modifies the supported SPP modes, leading to a deviation of the SPP modes from that supported by the planar structure. To have a clear understanding on the transmission properties of the hyperlens, a transfer matrix formulation for cylindrical hyperlens is developed, and the transmittance of the hyperlens is compared with that of the multilayered planar MD structures.

Although the cylindrical hyperlens can provide magnification, it has several drawbacks. Due to the cylindrical geometry, it can only give one-dimension sub-wavelength resolution and the image magnification is along the radial direction. In addition, it can only work under TM polarized light with the magnetic field along the cylinder axis. As a result, the image produced by a cylindrical hyperlens is distorted. These problems can be solved by hyperlens in a spherical shape. The idea of using

spherical hyperlens to realize two-dimension imaging has already been suggested [180, 181]. However, due to the difficulty in numerical simulations and fabrications, there are very limited studies on the imaging performance of such spherical hyperlens.

4.2 Imaging properties of the hyperlens

Figure 4.1 illustrates the schematic of the cylindrical hyperlens. It projects the image along the radial direction and mimics the function of an ordinary magnifying lens. The image can be magnified to a feature size above the diffraction-limit, which makes it possible to integrate such sub-wavelength imaging lenses with the conventional optical systems.

Figure 4.1 Schematic of the cylindrical hyperlens. The red arrows denote the image transfer direction.

The imaging mechanism of the hyperlens is similar to that of the multilayered planar MD structures, in which the super-guiding and transmitting of the evanescent waves play the dominant role. However, one significant difference between them is that the hyperlens not only transmits evanescent waves but also transforms them into propagating waves. The conversion of evanescent waves into propagating waves is resulted from angular momentum conservation [25], which can be defined by

$$m = k_{\theta} r \quad (4.1)$$

where m is the angular momentum mode number of an indecent cylindrical wave, k_{θ} is the tangential component of the wave vector and r is the radius. From equation 4.1, it

can be seen that as the waves are transmitted along the radial direction, the tangential wave vectors decreases gradually. It is possible to magnify the sub-wavelength information such that its smallest feature is larger than $\lambda/2$, thereby transforming the evanescent waves into propagating waves. As these propagating waves carry sub-wavelength information, it makes hyperlens capable of sub-wavelength imaging in the far-field. An immediate conclusion from equation 4.1 is that due to the conversion of evanescent waves in the imaging process, their optical properties may deviate from that of the planar case, especially for their transmission properties. To the best of our knowledge, there is no TMM for hyperlens reported. In order to understand the transmission properties of the hyperlens, in this section, the detailed formulation of the TMM in cylindrical coordinate is developed and presented.

4.2.1 TMM in cylindrical coordinates

The schematic diagram of a multilayered structure in cylindrical coordinate is illustrated in **Figure 4.2**. The principal axis of the structure is z -axis, and the permittivity of the i^{th} layer is denoted as ϵ_i . The total magnetic field along z -axis in i^{th} layer is denoted as the outgoing (H_{zi}^+) and ingoing (H_{zi}^-) waves, respectively. The wave solutions in cylindrical coordinate can be obtained from most of the standard text books on EM theory. This section will focus on the development of the TMM for the cylindrical hyperlens, the derivation procedure for propagating waves in cylindrical coordinate can be found in Reference [185]. In this work, the TMM for the evanescent waves is developed.

Figure 4.2 Illustration of a multilayered structure in cylindrical coordinate. The radius is denoted by r_n .

For TM polarized incidence ($H//z$ -axis), the total magnetic field in each layer can be denoted as the superposition of the ingoing and outgoing waves, and the magnetic field in layer i can be represented by

$$H_{zi} = H_{zi}^+ + H_{zi}^- = A_i H_m^{[1]}(kr) \exp(im\varphi) + B_i H_m^{[2]}(kr) \exp(im\varphi) \quad (4.2a)$$

for monochromatic propagating waves, and

$$H_{zi} = H_{zi}^+ + H_{zi}^- = A_i K_m(kr) \exp(im\varphi) + B_i I_m(kr) \exp(im\varphi) \quad (4.2b)$$

for monochromatic evanescent waves, where A_i and B_i are constants, m is the azimuthal number, $H_m^{[1]}$ and $H_m^{[2]}$ are the Henkel function of the first and second kind, respectively, and K_m and I_m are the modified Bessel and Henkel function. The electrical field along the azimuthal direction can be derived by solving the coupled Maxwell equations in cylindrical coordinate, and the total electric field along azimuthal direction in layer i can be represented by

$$E_{\varphi i} = E_{\varphi i}^+ + E_{\varphi i}^- = i \sqrt{\frac{1}{\epsilon_i}} A_i H_m^{[1]'}(kr) \exp(im\varphi) + i \sqrt{\frac{1}{\epsilon_i}} B_i H_m^{[2]'}(kr) \exp(im\varphi) \quad (4.3a)$$

for monochromatic propagating waves, and

$$E_{\varphi i} = E_{\varphi i}^+ + E_{\varphi i}^- = i\sqrt{\frac{1}{\varepsilon_i}} A_i K_m'(kr) \exp(im\varphi) + i\sqrt{\frac{1}{\varepsilon_i}} B_i I_m'(kr) \exp(im\varphi) \quad (4.3b)$$

for monochromatic evanescent waves. The above equations can be expressed as a basis of the magnetic field (H_{zi}^+, H_{zi}^-) , as shown below

$$\begin{pmatrix} H_{zi} \\ E_{\varphi i} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ i\sqrt{\frac{1}{\varepsilon_i}} \frac{H_m^{[1]'}(kr)}{H_m^{[1]}(kr)} & i\sqrt{\frac{1}{\varepsilon_i}} \frac{H_m^{[2]'}(kr)}{H_m^{[2]}(kr)} \end{pmatrix} \begin{pmatrix} H_{zi}^+ \\ H_{zi}^- \end{pmatrix} = M_{i_prop} \begin{pmatrix} H_{zi}^+ \\ H_{zi}^- \end{pmatrix} \quad (4.4a)$$

for propagating waves, and

$$\begin{pmatrix} H_{zi} \\ E_{\varphi i} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ i\sqrt{\frac{1}{\varepsilon_i}} \frac{K_m'(kr)}{K_m(kr)} & i\sqrt{\frac{1}{\varepsilon_i}} \frac{I_m'(kr)}{I_m(kr)} \end{pmatrix} \begin{pmatrix} H_{zi}^+ \\ H_{zi}^- \end{pmatrix} = M_{i_evan} \begin{pmatrix} H_{zi}^+ \\ H_{zi}^- \end{pmatrix} \quad (4.4b)$$

for evanescent waves. The remaining derivation processes for evanescent and propagating waves are exactly the same. For simplicity, the above matrices M_{i_evan} and M_{i_prop} are denoted as M_i in the following paragraphs.

The TMM requires the derivation of two important transfer matrices. The first matrix is M_i which converts the basis from (H_{zi}^+, H_{zi}^-) to $(H_{zi}, E_{\varphi i})$. The second matrix is the transfer matrix that accounts the phase shift and attenuation of the fields within layer i . For a layer bounded by radius r_{i-1} and r_i , the transfer matrix that account the phase shift and attenuation within layer i can be written as

$$\begin{pmatrix} H_{zi_ri}^+ \\ H_{zi_ri}^- \end{pmatrix} = \begin{pmatrix} \frac{K_m(kr_i)}{K_m(kr_{i-1})} & 0 \\ 0 & \frac{I_m(kr_i)}{I_m(kr_{i-1})} \end{pmatrix} \begin{pmatrix} H_{zi_ri-1}^+ \\ H_{zi_ri-1}^- \end{pmatrix} = P_i \begin{pmatrix} H_{zi_ri-1}^+ \\ H_{zi_ri-1}^- \end{pmatrix} \quad (4.5)$$

where P_i is defined as the transfer matrix which accounts the phase shift and attenuation within one particular layer. The final transfer matrix can be derived by applying the continuity equation of the tangential component of the electrical and magnetic field at each interface. Using the two transfer matrices M_i and P_i derived in

equations 4.4 and 4.5, the magnetic fields (H_{zn+l}^+ , H_{zn+l}^-) at the output surface can be expressed in term of the magnetic fields (H_{z0}^+ , H_{z0}^-) at the input surface. In matrix form, the final equation can be written as

$$M_0^{-1}M_1P_1^{-1}M_1^{-1}\cdots M_{n-1}P_{n-1}^{-1}M_{n-1}^{-1}M_n\begin{pmatrix} H_{zn+l}^+ \\ H_{zn+l}^- \end{pmatrix} = M\begin{pmatrix} H_{zn+l}^+ \\ H_{zn+l}^- \end{pmatrix} = \begin{pmatrix} H_{z0}^+ \\ H_{z0}^- \end{pmatrix} \quad (4.6)$$

where M is defined as the backward transfer matrix of the structure, and

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}. \quad (4.7)$$

As the light source is located in the inner radius, there will be no ingoing waves at layer $n+1$ ($H_{zn+l}^- = 0$). Based on equation 4.6, it is easy to show that the transmittance of the structure can be calculated by

$$t = \frac{1}{m_{11}} \quad (4.8)$$

4.2.2 Transmittance of the cylindrical hyperlens

Using the developed TMM formulation, the transmission curves of the hyperlens made of multilayered MD structures are calculated. To investigate the effect of radius on the transmittance of the hyperlens, the inner radius of the hyperlens is varied while the total thickness of the hyperlens is kept the same. Assume that the hyperlens consists of five pairs of MD layers (thicknesses of the individual metal and dielectric layers are both 20 nm) with a total thickness of 200 nm. The permittivity of the dielectric is 1, while Ag is assumed to be the metal with permittivity extracted from [120]. **Figure 4.3** shows the transmission curves of the hyperlenses with different inner radiuses. For comparison, the transmission curve of the equivalent multilayered planar structure is also plotted in the figure. The horizontal axis represents the tangential wave vector (k_θ for the hyperlens and k_x for the multilayered planar structure)

at the input surface of the structures. The incident wavelength in all calculations is 400 nm. The two arrows denote the center positions of the transmission curves of the planar structure, and the hyperlens with the inner radius $r=240$ nm, respectively.

The calculation results reveal that the transmission curves of the hyperlenses differ from that of the multilayered planar MD structure, and the inner radius plays an important role in determining its transmittance. Two features can be found from the calculation results (**Figure 4.3**). Firstly, the transmission curves of the hyperlenses shift toward larger tangential wave vectors as the inner radius decreases, although they have similar envelopes as that of the planar MD structure. Secondly, it is also found that the transmittance of the hyperlens decreases slightly as the inner radius decreases. The decreases in transmittance is due to the curved surface of the hyperlens, which reduces the energy density per unit volume as the light are transmitted towards the outer radius. The shift in the transmission curves can be explained by the compression ratio of the tangential wave vectors. The theoretical compression ratio of the tangential wave vectors of the hyperlens with an inner radius of 240 nm is calculated by equation 4.1. Due to angular momentum conservation, the incident tangential wave vectors are compressed by 1.8 times when they are transmitted from the inner radius (240 nm) to the outer radius (440 nm). As shown in **Figure 4.3**, the compression ratio of the tangential wave vectors can be estimated by measuring the relative shift of the transmission curves, which is about 1.79 ($3.75/2.1 \approx 1.79$). The calculations match perfectly with the angular momentum conservation rule, which indicates that the TMM formulation is correct. When the inner radius is comparable to the incident wavelength (e.g. $r=240$ nm), the amount of the shift in the transmission curve is significant. A direct consequence of the shift in the transmission curve is the increases of the accessible range of the tangential wave vectors. This means that the resolving

power of the hyperlens is related to its inner radius and outer radius, and it is higher than that of the planar structure. Thus, in order to achieve a higher resolution, the inner radius of the hyperlens should be as small as possible. However, as the imaging area of the hyperlens is only limited to the inner radius, there is a tradeoff between the maximized imaging area and the maximized resolving power. In order to have a sufficient imaging area, the inner radius cannot be very small.

Figure 4.3 Transmission curves of the hyperlenses with different inner radius and the equivalent multilayered planar structure.

4.2.3 Resolving power of the hyperlens versus multilayered planar MD lens

From the transmission curves of the hyperlens in **Figure 4.3**, it is shown that the higher resolution should be achieved by hyperlens compared with its equivalent multilayered planar MD lenses. In this section, the resolving power of the hyperlens is investigated numerically. **Figure 4.4** illustrates the configuration of the simulated structures. All the studied lenses are made of 10 pairs of Ag-X with a total thickness of 300 nm. The inner radii of the two hyperlenses are 240 nm and 440 nm, respectively. A 50 nm thick Cr mask layer is covered on the input surface of the lenses, and two 30 nm wide slits with a center to center distance of 80 nm are being imaged. The metal filling ratios in all the lenses are kept as 0.428, which is the corresponding

optimized filling ratio for the incident wave at 400 nm. The permittivity of the Cr and Ag are extracted from reference [120], while the permittivity of the dielectric X is assumed as 5. The maximum mesh size of the lens region and the surrounding region are 1 nm and 2 nm, respectively. The boundaries of the simulation domain are set as PMLs to reduce the influence of the backscattered waves.

Figure 4.4 Configuration of the simulated hyperlens when two 80 nm spaced slits are being imaged. To show the details of the hyperlens, the dimensions of the simulated structure in the figure are not scaled.

Figure 4.5 shows the simulation results. From the figure, it can be seen that as the inner radius r decreases, the resolving power of the hyperlens becomes higher. The two 80 nm spaced slits can be clearly resolved by the hyperlens with an inner radius of 240 nm, while the planar MD lens fails to resolve them.

Figure 4.5 Comparison of the resolving power of the planar MD lens and the hyperlens. (a)-(c) Energy flow distribution in the planar MD lens and the hyperlens. (d) PSFs of the images measured at the output surface of the lenses.

To conclude, the TMM developed in this work provides sufficient information in revealing the transmission properties of hyperlens. Based on the transmission curves calculated by the TMM, it is clear that the transmission properties of the hyperlens deviate from those of the planar structures. As a result of angular momentum conservation, the transmission curves of the hyperlens shift toward longer tangential wave vectors. The resolving power of the hyperlens is better than that of the planar MD structure and is inversely related to the inner radius. Thus, in order to achieve a higher resolution by the hyperlens, the inner radius should be kept small.

4.2.4 Validity of the FoM for hyperlens

Although the transmission of the hyperlens is different from the multilayered planar MD lenses, the imaging mechanism in hyperlens is still based on the super-guiding and transmitting of the evanescent waves. Thus, it is possible to use the FoM

that developed in Chapter 3 to figure out the optimized filling ratio of the hyperlens. Considering a hyperlens consists of 10 pairs of Ag-X, the inner radius and outer radius of the hyperlens are 240 nm and 540 nm, respectively. Based the FoM, the optimized filling ratio the hyperlens under 400 nm incidence is $p=0.428$. With the configuration as illustrated in **Figure 4.4**, the validity of the FoM is numerically evaluated. **Figure 4.6** shows that the best performance of the hyperlens evaluated in terms of the maximum intensity and minimum FWHM are 0.31 and 0.41, respectively. Due to the finite number of the Ag-X layers and the curved surface of the hyperlens, the optimized filling ratio evaluated in terms of the maximum intensity deviate some more from the theoretical value. However, it is found that the optimized filling ratio evaluated in terms of the minimum FWHM is very close to the theoretical value. This indicates that the waveguiding mechanism in the hyperlens is still the same as that of the planar MD structures. Since for imaging purposes, it is more concerned with the resolution of the lenses, the proposed FoM should be sufficient to be used as a guideline for the design and fabrication of such lenses.

Figure 4.6 Numerical optimization of the filling ratio of the hyperlens consists of 10 pairs of Ag-X. The imaging performance of the lenses evaluated in terms of (a) Intensity, and (b) FWHM of the PSF.

4.3 Imaging properties of the hemispherical hyperlens

Due to the cylindrical geometry, the cylindrical hyperlens only provides one-dimensional magnification along the radial direction, and it only works with TM polarized incident light with $H \parallel z$ -axis. To overcome these limitations, the hemispherical hyperlens is investigated in this project. The hemispherical hyperlens works on linearly polarized light in any polarization direction, and the image can be magnified isotropically along radial direction. This is a significant improvement from the cylindrical hyperlens.

The geometry of the simulated hemispherical hyperlens is illustrated in **Figure 4.7**. It consists of 10 pairs of hemispherical Ag-X embedded in a quartz substrate. The filling ratio of Ag is obtained by the FoM, which is 0.428 for incident light of 400 nm. The top and the inner shell of the hemispherical hyperlens are covered with a 50 nm thick Cr layer. An annular silt with an inner radius of 30 nm and outer radius of 60 nm is opened on the Cr mask. In the simulations, the maximum mesh size of the Ag-X layers, the annular silt and the quartz substrate are 8 nm, 10 nm and 40 nm respectively. The dimension of the simulation domain is 1000 nm $\times$ 1000 nm $\times$ 600 nm. The boundaries except the incident boundaries are set as scattering boundary condition.

Figure 4.7 Schematic of the simulated hemispherical hyperlens. The illustrated hemispherical hyperlens is in Cartesian coordinates, with the center of the hemispherical Ag-X layers located at the origin.

The imaging properties of the hemispherical hyperlens under a linearly polarized light are investigated. The energy distributions for linear polarized light with the electric field along different directions are simulated. **Figure 4.8** shows the energy distributions at the image plane located at $z=-550$ nm. It can be seen that, for a 400 nm normally incident light with electric field along the x -axis, only a small portion of the annular slit is resolved, as illustrated in **Figure 4.8 (a) and (b)**. The resolved portions of the annular slit are along the electric field direction. These phenomena can be explained by investigating the degree of the SPPs excited by the annular slit. Since the image transfer process in such layered MD structures relies on the coupling of the excited SPP modes on the MD interfaces, the strength of the SPPs excited by the annular slit affect the image quality. As SPPs are solutions of Maxwell's equations that represent TM waves, the coupling efficiency of the incident light with SPP modes depends on the incident direction, so do the images formed by the hemispherical hyperlens. Along the x -axis, the incident is TM polarized for the portions of the annular slit around $y=0$. Excitation of SPPs is most efficient around these regions. Therefore, these portions can be resolved, as seen from the two light spots at points A_1 and A_2 illustrated in **Figure 4.8 (b)**. Contrarily, along the y -axis, the incident light becomes TE polarized for the portions of the annular slit around $x=0$. Excitation of the SPPs is least efficient near these regions. Hence these portions cannot be resolved, as seen from the two blurred regions at points B_1 and B_2 in **Figure 4.8 (b)**. Such phenomena have also been obtained by changing the electric field direction of the incident light to other directions, as shown in **Figure 4.8 (c)-(f)**. Thus, under linearly polarized light illumination, the hemispherical hyperlens can only resolve portions of an object along the electric field direction.

Figure 4.8 Imaging of an annular slit under a 400 nm linearly polarized light illumination. (a) with the electric field along the positive x -axis direction from the 3-dimensional view, (b) image in Fig. 2(a) from the two-dimensional view, (c) with the electric field 22.5° from the positive x -axis direction, (d) with the electric field 45° from the positive x -axis direction, (e) with the electric field along the y -axis direction, (f) with the electric field 135° from the positive x -axis direction.

The above simulations indicate that the resolved portion of the object depends on the polarization direction of the incident light and only these portions of the object along the electric field direction can be resolved. Thus, it is possible to recover the entire image by superposing sufficient number of images obtained under differently linearly polarized light. As shown in **Figure 4.9**, when the number of the images obtained with different polarization directions being superposed is increased, the details of the annular ring become much clearer. From the figure, it is also found that there is only minor difference between the image in **Figure 4.9 (b)** produced by superposing four images and the image in **Figure 4.9 (c)** generated by superposing eight images. Although the image quality can be improved by superposing a greater

number of images obtained with differently polarized light, superposing four images is enough to recover the details of the object.

Figure 4.9 Superposition of the images obtained with electric field (a) along the x -axis and y -axis; (b) along the x -axis, 45° from the positive x -axis, y -axis, and 135° from the positive x -axis; (c) along the x -axis, 22.5° from the positive x -axis, 45° from the positive x -axis, 67.5° from the positive x -axis, y -axis, 112.5° from the positive x -axis, 135° from the positive x -axis, and 157.5° from the positive x -axis.

Numerical simulation is carried out to further verify the superposition method by simulating an asymmetric object. The object is an "E" pattern centered at the inner radius of the hyperlens. The line width and the height of the "E" pattern are 30 nm and 210 nm, respectively. **Figure 4.10** illustrates the final image generated by overlapping 4 images obtained with the electric field along the x -axis, 45° from the positive x -axis, y -axis, and 135° from the positive x -axis. It can be seen that the "E" pattern is clearly resolved at the output surface of the hemispherical lens. This confirms that the proposed superposing method can be used to generate a complete image of the object under observation.

Figure 4.10 Imaging of an "E" pattern by the hemispherical hyperlens at 400 nm.

The above superposition method provides a feasible solution to generate a complete image of the object under investigation. However it is only suitable for static objects. In real-life applications, especially for biological applications which involve the investigation of living machineries such as cells and viruses, the superposition method may not work well. Since these living machineries constantly move, the superposition method may generate distortions if the images obtained with different polarized light rays are not captured continuously in a very short period. To address this issue, instead of taking the superposition of many images obtained under different polarization directions, a rotational linearly polarized light source or unpolarized light can be used.

4.4 Limitations of the hyperlens

The hyperlens provides a convenient way to realize far-field sub-wavelength imaging with magnification. However, it has several drawbacks. Besides the low transmission efficiency caused by material absorption, another major problem of the hyperlens is the limited imaging area and the non-planar input surface. In order to achieve enough geometric magnification, the inner radius of the hyperlens is usually kept small. The input surface of the hyperlens is only limited to the inner radius of the curved multilayered MD structure, which only covers a small area in the scale of the

incident wavelength. In addition, its non-planar input surface also makes it difficult to imaging solid objects that are not deformable. Another limitation of the hyperlens is that the object has to be placed very close to the inner surface of the hyperlens, which limit the imaging depth as well.

Despite these problems, the hyperlens is the first metamaterial lens that is capable of far-field sub-wavelength imaging with magnification. It is an excellent design to provide geometric magnification using plasmonic metamaterial lenses. In the future, the imaging area of the hyperlens may be increased when the material absorption is no longer a concern. This kind of hyperlens may possibly be integrated with conventional optics for real time sub-wavelength imaging. Hyperlenses may also find applications in other areas, such as nanofabrication, sensing and data storage.

4.5 Summary

The transfer matrix method formulation in cylindrical coordinates is developed. The transmission curves calculated by the TMM show that the transmission curve is different from the planar case, the accessible range of the tangential wave vectors in hyperlens is larger than the planar case. Thus the hyperlens should have higher resolution. Numerical simulations showed that, for hyperlens and planar MD lenses with the same optimized filling ratio, the resolving power of the hyperlens is higher than that of the planar lens.

The imaging performance of the hemispherical hyperlens is numerically investigated. Two-dimensional sub-wavelength imaging with the hemispherical hyperlens is demonstrated. Superposition of the images obtained under different polarization directions is proposed so that a complete image of the object can be

obtained. In addition, a rotational linearly polarized light or unpolarized light is suggested to generate a full image of the object.

Chapter 5. Waveguiding and imaging by dielectric nanorod chain

In this chapter, a nanoscale waveguide by a closely-spaced dielectric nanorod chain embedded in the metal is proposed, and a pixel-to-pixel lens made of a two-dimensional array of dielectric nanorod chains is demonstrated. Section 5.1 briefly introduces the background and motivations of the work. In section 5.2, a nanocircuit model is proposed to quantitatively investigate the waveguiding properties of the dielectric nanorod chains embedded in the metal and its complementary structure—the metallic nanorod chains embedded in dielectric. Section 5.3 presents the numerical studies of the metallic/dielectric nanorod chains. Section 5.4 describes sub-wavelength imaging capability of a pixel-to-pixel lens constructed by the dielectric nanorod chains. With such kind of lenses, much better performance in terms of the resolution and transmission can be achieved.

5.1 Introduction

Since the theoretical proposal of the perfect lens by Pendry [7], the superlens, multilayered MD structures and metallic nanowires have been extensively investigated for their sub-wavelength imaging capabilities [9, 20, 21, 23, 25, 27-30]. The imaging performances of these plasmonic metamaterial lenses are primarily affected by the image spreading at the input surface, the cross-talk among transmission channels, and inherent losses. The performances of these lenses can be improved by optimizing the structure designs, but the improvement is very limited. Although the metallic nanowire structures demonstrated better performances in terms of resolution and image transmission distance compared to the multilayered MD structures [27-29, 186-189]. The guided plasmon modes on the metallic nanowires can extend some distance into

the dielectric region and couple with adjacent transmission channels, which results cross-talk and image spreading.

Other than the metallic nanowires, a well-known structure that is capable to transport the EM energy below the diffraction-limit is a linear chain of metallic nanoparticles [33, 61, 84-89, 155, 190, 191]. When the metallic nanoparticles are spaced close together, the distance dependent near-field term in the expansion of the electric dipole interaction dominates, which leads to the excitation of coupled plasmon modes and coherent transportation of the energy along the chain [84, 192-194]. The excitation of LSPs and the strong near-field interaction between metallic nanoparticles lead to better confinement of energy [34, 85, 86]. Compared to the metallic nanowires, one advantage of the metallic nanoparticle chain is the flexibility in tuning its optical properties by varying its constituent materials or geometry [61, 195, 196]. The extra degree of freedom over the control of the optical properties gained in metallic nanoparticle chain structure makes it very attractive for waveguiding with desired functionalities. Several groups demonstrated sub-wavelength imaging using the metallic nanoparticle chain scheme [34-36, 197]. However, as the transmission channels in such lenses are separated by the lossless dielectrics, the excited surface plasmon modes on each transmission channel can extend several tens of nanometers into the dielectric background. The cross-talk remains as a problem in such lenses with metal as the transmission channels.

Besides the metallic nanoparticles, it has been reported that its complementary structure, the metallic nanocavities (dielectric nanoparticles embedded in the metal) can also sustain LSPs akin to that of the metallic nanoparticles [61, 92-94, 198]. This means that LSPs can be excited in a completely confined space, which makes it possible to achieve better energy confinement. The LSPs in such systems are also

named cavity plasmons or void plasmons. Many intriguing optical properties associated with cavity plasmon based structures, such as strong light-matter interaction, total energy absorption and strong field enhancement have been reported [92, 93]. Both theoretical and experimental studies of the LSPs in such nanocavities were carried out [94-97]. Based on the knowledge on metallic nanoparticle waveguides, a linear chain of such metallic nanocavities could be possibly used as a nano-sized waveguide as well. For a lens constructed by such metallic nanocavity chains, the transmission channels are separated by the lossy metals, which may lead to a significant reduction of the cross-talk among image channels. In contrast to previous proposed plasmonic metamaterials lenses, the metallic nanocavity chain uses the lossless dielectric as the major transmission channel, which may also lead to longer image transmission distance. In addition, although the metallic nanoparticle chains have been widely studied over the past decades, there is very limited study on the waveguiding properties of such metallic nanocavity chains.

In the first part of this chapter, the waveguiding properties of the metallic nanocavity chains are investigated and compared with the metallic nanoparticle chains. In the second part of this chapter, based on the understanding of the waveguiding properties of the metallic nanocavity chains, a pixel-to-pixel lens constructed by a two-dimensional metallic nanocavity chains (dielectric nanorod chains embedded in the metal) is proposed and numerically investigated.

5.2 Waveguiding properties of the metallic/dielectric nanorod chains

5.2.1 Metallic nanoparticles/nanocavities in two-dimensional space

5.2.1.1 Metallic/dielectric nanorod chains

Metallic nanoparticles/nanocavities provide three-dimensional surface wave confinement, but waveguides made of such metallic nanoparticles/nanocavities are difficult to be realized. For the simplest metallic nanoparticles/nanocavities in a spherical shape, despite the difficulties in synthesis of such nanospheres with accurate shape and diameter, it is also a challenging task to accurately position the nanospheres into a well-defined pattern.

Fabrication of nanostructures of the desired shape and physical properties is a task of great importance for modern electronics, sensors, nanophotonics, and so forth. Over the years, different methods have been developed to prepare various nanostructures, including metallic nanoparticles and nanowires [199-206]. These fabrication methods can be either bottom-up approach or top-down approach. A bottom-up approach synthesizes the metallic nanoparticles or nanowires by combining constituent adatoms. Usually, the bottom-up approach is based on chemical or electrochemical reactions, which is the most popular synthesis technique. The advantage of the bottom-up approach is that large assemblies of nanoparticles or nanowires can be fabricated. For example, metallic nanoparticles of various sizes can be easily produced by the reduction of a metal salt in solution [199]. Chemical method has become one of the most popular methods to produce metallic nanoparticles, and metallic nanoparticles of various sizes are commercially available. Metallic nanowires can be fabricated using many chemical reaction based methods as well [207]. Growth of nanowires based on the bottom-up approach usually relies on catalysts (e.g. metallic nanoparticles) to control the growth. In this method, the catalysts are deposited on the

sample, and then the nanowires are grown by using the catalysts as a precursor to control the growth. The quality of the nanowires depends on the catalysts, as well as the chemical reactions. Fabrication of nanowires is a challenging task due to the difficulty in controlling the aspect ratio, crystalline quality, morphology, and the alignment of nanowires [207]. Although there has been significant advancement recently made in fabricating nanowires, nanowires are still far from practical applications. Thus, for the bottom-up approach, there are more difficulties in fabricating the nanowire than the nanoparticle.

In addition to the bottom-up approach, the top-down approach also plays an important role in the fabrication of nanoparticle and nanowires. This method uses the predefined nanostructures as the templates to growth the nanostructure. As the template defines the geometry of the nanostructure, highly ordered nanostructures can be realized. The templates can be prepared by various methods, such as the chemical method (e.g. nanoporous membrane such as anodized alumina oxide (AAO) and porous silicon) and current nanofabrication techniques (e.g. electron beam lithography (EBL) and focused ion beam lithography (FIB)). For top-down approach, fabrication of suitable templates is clearly a critical step. To date, a number of methods have been developed to fabricate various negative templates. Examples include the AAO, porous silicon, polycarbonate membranes, and mica sheets. These templates contain a large number of ordered cylindrical nanopores, and nanopores of various diameters can be easily fabricated. While for the case of nanoparticles, the templates that can be used are very limited. Most of the templates that used to fabricate nanoparticles are fabricated by nanofabrication techniques [207], and the size and shape of the templates for are difficult to control. Although the fabrication of metallic nanoparticles in a large assemble can be achieved by many methods, accurate positioning of the individual

particles in a well-defined pattern is difficult. Currently, the best way to arrange an array of nanoparticles in a defined shape is by template-assisted growth. However, fabrication the nanoparticle templates by current nanofabrication technique is a very challenging task. Thus, for the top-down approach, there are more difficulties in fabricating the nanoparticles than the nanowires.

As in this work, the nanoparticles/nanocavities are intended to be used as a waveguide with very a very accurate position. Template-assisted growth is one of the best solutions to fabricate such structures. Due to the difficulties in fabricating ordered nanoparticles using template-assisted growth, it is more practical to consider such devices of two-dimension first and then extend them into three-dimension. In addition, the study of the two-dimensional structures also helps to understand the physics of higher dimensional systems. The two-dimensional metallic nanoparticle and metallic nanocavity in this thesis are the metallic nanorod embedded in dielectric and dielectric nanorod embedded in the metal, respectively. They are called metallic nanorod and dielectric nanorod, respectively, for simplicity. The metallic/dielectric nanorods are assumed to be infinite long in z -axis, and the waveguiding in such metallic/dielectric nanorod chains refers to the energy propagation along the chain (y -axis), as illustrated in **Figure 5.1**.

Figure 5.1 Illustration of a linear chain waveguide consisting of closely-spaced metallic/dielectric nanorods. The red arrow denotes the energy flow direction along the chains.

5.2.1.2 LSPs on single metallic/dielectric nanorod

The underlying phenomena and physics of the metallic/dielectric nanorod can be analyzed by means of the quasi-static approximation [61, 152, 208, 209]. Although it is an over simplified model, it is sufficient to reveal some of the key properties of the metallic nanostructures [61, 89, 90, 210, 211]. As a starting point, the polarizabilities of the metallic/dielectric nanorod are investigated first by the quasi-static approximation. The polarizabilities of the metallic/dielectric nanorod can be derived by treating them as ellipsoids. Considering the semi-axis of an ellipsoid in the three orthogonal directions (x , y and z) a , b and c , respectively, the polarizability α in each axis direction can be evaluated by [208]

$$\alpha = \frac{4}{3} \pi abc \frac{\epsilon_m - \epsilon_d}{\epsilon_d + L_{a,b,c} (\epsilon_m - \epsilon_d)} \quad (5.1)$$

where $L_{a,b,c}$ is a geometry dependent depolarization factor. It measures how much the internal field within the ellipsoid is weakened by the polarization. The depolarization factor $L_{a,b,c}$ can be expressed in term of the eccentricity e [208]. For prolate spheroids ($a=b<c$), the depolarization factors can be calculated by

$$L_c = \frac{1-e^2}{2e^3} \left(\ln \frac{1+e}{1-e} - 2e \right) \quad (5.2a)$$

and

$$L_a = L_b = \frac{1}{2} (1 - L_c) \quad (5.2b)$$

where the eccentricity of the ellipsoid is $e = \sqrt{1 - c^2/a^2}$. For oblate spheroids ($a=b>c$), the depolarization factor can be calculated by

$$L_c = \frac{1+e^2}{e^3} (e - \tan^{-1} e) \quad (5.3a)$$

and

$$L_a = L_b = \frac{1}{2}(1 - L_c) \quad (5.3b)$$

where the eccentricity of the ellipsoid is $e = \sqrt{1 - a^2/c^2}$. The three depolarization factors for any ellipsoid also satisfy the following relation

$$L_b + L_a + L_c = 1 \quad (5.4)$$

For a long metallic nanorod with the cylindrical axis along the z -axis, it corresponds to the extreme case of the prolate spheroids ($a=b \ll c$). The three depolarization factors for an infinite long metallic nanorod are $(1/2, 1/2, 0)$. By substituting the three depolarization factors to equation 5.1, the polarizability of a long metallic nanorod in the direction perpendicular to its cylindrical axis (z -axis) is

$$\alpha = \frac{8}{3} \pi abc \frac{\epsilon_m - \epsilon_d}{\epsilon_m + \epsilon_d} \quad (5.5)$$

For a long dielectric nanorod embedded in the metal, its polarizability can be obtained by carrying out the substitutions $\epsilon_m \rightarrow \epsilon_d$ and $\epsilon_d \rightarrow \epsilon_m$ in equation 5.5. Thus the polarizability of a dielectric nanorod embedded in metal in the direction perpendicular to its cylindrical axis is

$$\alpha = \frac{8}{3} \pi abc \frac{\epsilon_d - \epsilon_m}{\epsilon_d + \epsilon_m} \quad (5.6)$$

It can be seen from equations 5.5 and 5.6 that the Frohlich conditions of the metallic/dielectric nanorods can be met when $Re(\epsilon_m) = -\epsilon_d$. Thus localized plasmon resonance oscillating in the plane perpendicular to the cylindrical axis is supported by both structures. The excitation of LSP modes on the metallic/dielectric nanorods serves as the basis for energy confinement below the diffraction-limit. It should also be noted that the quasi-static approximation corresponds to a dipole plasmon mode, which does not account the higher order plasmon modes in the nanostructure. For practical systems, the higher order plasmon modes always exist due to the presence of

high spatial frequency components [212-214]. Although many works used the dipole plasmon mode approximation to reveal several key aspects of some metallic nanostructures [90, 215-220], they have the stringent requirement on the geometry of the nanostructure and type of excitation (e.g. homogeneous excitation). When studying a practical system, careful considerations should be exercised, especially for complicated structures in which the optical properties might be affected by higher order plasmon modes. For closely spaced nanorods (i.e. $d \approx 2r$), the excited plasmon modes become more complicated and the multipole plasmon modes supported by the nanorod start to interact with their counterparts. These multipole plasmon modes give rise to new channels for energy transfer. Thus, when studying the waveguiding properties of the closely-spaced metallic nanostructures, the role of multipole interactions should also be taken into consideration.

5.2.2 Nanocircuit model for closely-spaced metallic/dielectric nanorod chains

This section focuses on investigation of the waveguiding properties of closely-spaced metallic/dielectric nanorod chains, with an intention to use them for sub-wavelength imaging. For imaging purpose, the external excitations are essentially localized, and the dipole approximation may not be sufficient to reveal the properties of the waveguide accurately. The nanocircuit model has been widely used in design and investigation of transmission-line metamaterials in microwave frequencies [221-223]. The nanocircuit model has shown great potential in engineering and tailoring light-matter interactions in complex systems. Recently, it has also been shown that the nanocircuit model could be possibly extended into optical regime for plasmonic applications [225]. By employing the nanocircuit model, it is possible to construct an equivalent nanocircuit based on the type of near-field interactions. Thus in this work,

the nanocircuit model is employed to quantitatively evaluate the energy transport in the metallic/dielectric nanorod chains.

5.2.2.1 Type of near-field interactions in closely-spaced nanostructures

The near-field interaction plays an important role in the energy transfer processes along closely-spaced nanostructures. In order to obtain the nanocircuit model, we have to understand the type of near-field interactions first. Depending on the polarization direction of the external EM field, the near-field interactions in a linear chain of closely-spaced metallic/dielectric nanorods can be divided into two types. For the external EM waves with the electric field parallel to the energy propagation direction (longitudinal polarization), the near-field interactions are dominated by the Coulomb interactions in the longitudinal direction. For the external EM waves with the electric field perpendicular to the energy propagation direction (transverse polarization), the near-field interactions are dominated by the Coulomb interactions in the transverse direction. The near-field interactions of the metallic/dielectric nanorod chains under longitudinal polarization and transverse polarization are illustrated in **Figure 5.2**.

Figure 5.2 Illustration of the near-field interactions in the metallic/dielectric nanorod chains under different polarization directions. The first row illustrates the type of near-field interactions in metallic nanorod chains under (a) transverse polarization and (b) longitudinal

polarization. The second row illustrates the type of near-field interactions in dielectric nanorod chains under (c) transverse polarization and (d) longitudinal polarization.

5.2.2.2 Nanocircuit model for metallic/dielectric nanorod chains

The interaction of the metallic/dielectric nanorod chains with external excitations can be described by a network of optical lumped circuit elements [221-223]. This means that the optical elements in metallic/dielectric nanorod chains can be modeled by the equivalent RLC (an electrical circuit consisting of a resistor (R), an inductor (L), and a capacitor (C), connected in series or parallel) circuit elements [223]. For the metallic/dielectric nanorod chains, the inductance elements can be composed of the metallic nanorods or the metal spacer layers between two dielectric nanorods. The capacitive elements can be composed of dielectric nanorods or the gaps between two metallic nanorods. To illustrate the idea, **Figure 5.3** shows the equivalent nanocircuits of the metallic/dielectric nanorod chains by considering only dipole interactions [224]. It should be noted that the equivalent nanocircuits for multipole interactions will be different, but they can be constructed in a similar way. The nanocircuit model for metallic nanorod chain under longitudinal polarization and dielectric nanorod chain under transverse polarization are illustrated in **Figure 5.3 (a)**. The nanocircuit consists of series inductors and shunt capacitors, which is a typical right-handed transmission line configuration. In comparison, the nanocircuit models for metallic nanorod chain under transverse polarization and for dielectric nanorod chain under longitudinal polarization are illustrated in **Figure 5.3 (b)**. In this case, the equivalent nanocircuit consists of series capacitors and shunt inductors, which corresponds to a left-handed transmission line configuration. Based on the knowledge on right-handed and left-handed transmission lines, we can immediately know that the two configurations in **Figure 5.3 (a)** support forward-wave propagation which has a higher transmission

efficiency. In contrast, the two configurations in **Figure 5.3 (b)** support backward-wave propagation which has lower transmission efficiency. In order to achieve a high transmission, metallic nanorod chain should be employed if the incident light is in longitudinal direction, but dielectric nanorod chain should be used if the incident light is in transverse direction. It should be mentioned that the material loss can also be taken into the account by the nanocircuit model. The material loss corresponds to the presence of additional resistances, which reduces the strength of the resonance and the overall propagation length. It can be seen that although the nanocircuit paradigm is simple, it provides many insight on the optical properties of the plasmonic waveguide structures.

Figure 5.3 Nanocircuit models for the metallic/dielectric nanorod chains under different polarization directions [224]. (a) First row: equivalent nanocircuit (right-handed transmission line). Second row: metallic nanorod chain under longitudinal polarization. Third row: dielectric nanorod chain under transverse polarization. (b) First row: equivalent nanocircuit (left-handed transmission line). Second row: metallic nanorod chain under transverse polarization. Third row: dielectric nanorod chain under longitudinal polarization.

5.2.3 Numerical simulations

5.2.3.1 The structure

Numerical simulations are carried out to investigate the waveguiding properties of the metallic/dielectric nanorod chains. The schematic of the simulated dielectric

nanorod chain is illustrated in **Figure 5.4**. It is one linear chain of dielectric nanorods embedded in a metallic substrate. The dielectric nanorods are made of silicon dioxide (SiO_2). The radius of the dielectric nanorod, the inter-nanorod distance and the metal spacer layer are denoted as r , d and h , respectively. The metal spacer layer refers to the metal region between the two adjacent dielectric nanorods, and it has the same value to that of the surface-to-nanorod distance. The structure of the metallic nanorod chain can be deduced by exchanging the metal and SiO_2 . In the numerical simulations, a point-dipole source ($H||z$ -axis) is used as the local excitation to inject the EM energy into the metallic/dielectric nanorod chain. In order to improve the coupling efficiency of the point source with the metallic/dielectric nanorod chains, the point-dipole source is placed at the plane 5 nm from the surface of the substrate. In the following discussion, unless otherwise stated, SiO_2 is assumed dispersion-less over the spectrum of interest with a permittivity of 2.2, while the metal is modeled as silver with experimental permittivity extracted from reference [120].

Figure 5.4 Schematic of the dielectric nanorod chain embedded in metal. The point-dipole source is TM polarized with the magnetic field along z -axis.

5.2.3.2 Response of a single metallic/dielectric nanorod to a point-dipole source

To have an overall understanding on how the metallic/dielectric nanorod chain interacts with a localized point-dipole source, the structure that consists of only one

metallic/dielectric nanorod are investigated first. The responses of the metallic/dielectric nanorod under both longitudinal and transverse polarizations are investigated. In the numerical simulations, the transmission spectra are used to qualitatively evaluate the strength of the excited plasmon modes and they are obtained from the electrical field strength ($|E|^2$) at the output surface (denoted by the blue dot in **Figure 5.4**). An electric point dipole with a magnitude of 1×10^{-13} mA is used as the excitation source. The dimensions of the simulation domain are $3000 \text{ nm} \times 3000 \text{ nm}$, with all the boundaries set as PML to reduce the influences of the back scattered waves. The maximum mesh size for the metallic/dielectric nanorod, the substrate and the vacuum are 0.5 nm, 1 nm and 2 nm, respectively. For single metallic/dielectric nanorod with $r=20 \text{ nm}$ and $h=3 \text{ nm}$, their transmission spectra are plotted in **Figure 5.5 (a)** and **(b)**, respectively.

From **Figure 5.5 (a)**, it can be seen that the transmission peaks of the single metallic nanorod under both longitudinal and transverse polarizations are located around $\lambda=350 \text{ nm}$, which is about the theoretical value 360 nm calculated by equation 5.5. For the single dielectric nanorod embedded in the metal, two transmission peaks centered at $\lambda=400 \text{ nm}$, and $\lambda=515 \text{ nm}$ are observed for transverse polarization, and one transmission peak centered at $\lambda=410 \text{ nm}$ is observed for longitudinal polarization. From equation 5.6, the dipole plasmon resonance wavelength of such a dielectric nanorod embedded in the metal should be the same as that of the metallic nanorod. This indicates that the excited plasmon modes in the single dielectric nanorod embedded in the metal are no longer dipole excitation.

Figure 5.5 Transmission spectra and charge distributions of single metallic/dielectric nanorod for longitudinal and transverse polarizations. Transmission spectra of the (a) metallic nanorod embedded in dielectric, (b) dielectric nanorod embedded in metal. Charge distributions at the corresponding transmission peaks: (c) metallic nanorod embedded in dielectric, (d) dielectric nanorod embedded in metal.

The charge distributions at the corresponding transmission peaks are examined and schematically plotted in **Figure 5.5 (c) and (d)** to have a better understanding of the excited plasmon modes around these transmission peaks. It is found that, for longitudinal polarization, the charge distributions in both structures deviate from that of an ideal dipole excitation (first row of **Figure 5.5 (c) and (d)**). Since a localized point-dipole source is used to inject the EM energy, the strong near-field interaction causes the charge distributions deviating from that of an ideal dipole excitation. Moreover, the degree of deviation is much larger for the single dielectric nanorod embedded in the metal. This is because dielectric nanorod embedded in the metal

interacts with the external excitations more efficiently than the metallic nanorod of the same geometry [93]. Due to the finite thickness of the metal spacer layer h , the point-dipole source interacts strongly with the excited plasmon modes inside the dielectric nanorod embedded in the metal. And the strong near-field interaction modifies the charge distributions and causes the resonance wavelength to shift from that of an ideal dipole excitation. The above analysis can be verified by numerical simulations with significantly increased metal spacer layer thickness. **Figure 5.6** shows the transmission spectra and charge distributions of the dielectric nanorod with $h=100$ nm. It clearly shows that the transmission peaks of the dielectric nanorod under both polarizations are centered at around the theoretical wavelength 360 nm. Thus the thickness of metal spacer layer plays an important role in controlling the excited plasmon modes of the dielectric nanorod embedded in the metal.

Figure 5.6 Transmission spectra and charge distributions of the single dielectric nanorod embedded in metal under longitudinal and transverse polarizations. (a) Transmission spectra. (b) charge distributions at $\lambda=360$ nm.

Under transverse polarization, the charge distributions of the single metallic nanorod are strongly localized at the side next to the point-dipole source, while, for the single dielectric nanorod embedded in the metal, the charge distributions at 400 nm

show a typical quadrupole excitation instead of dipole excitation. For the transmission peak located at 515 nm, its charge distribution resembles two parallel dipole excitations localized around the metal spacer layer. The quadrupole excitation at 400 nm and the two parallel dipoles excitation at 515 nm are associated with the finite thickness of the metal spacer layer h and the closely-spaced point-dipole source. As shown in **Figure 5.6 (a)**, when the metal spacer layer is increased to 100 nm, only one transmission peak is observed at $\lambda=360$ nm. It can be seen that the metal spacer layer plays a very important role in the light-matter interaction process for the dielectric nanorod embedded in the metal. When it is much smaller than the skin depth of the metal, the excited plasmon modes will be affected significantly as a result of the strong near-field interactions.

Another interesting finding from the transmission spectra is that the peak transmission efficiency of the single dielectric nanorod embedded in the metal is much higher than that of the metallic nanorod, as shown in **Figure 5.5 (a)** and **(b)**. To explain the high transmission of the dielectric nanorod embedded in the metal, the theoretical model developed by Teperik [93] can be referenced. To derive an analytical equation, Drude model is used to describe the permittivity of the metal. The transmittance T and absorbance A of a dielectric nanorod buried in a metallic substrate around its l -th plasmon mode can be described by the following formula

$$T \approx \frac{\left(\gamma_l^{(f)}\right)^2}{\left(\omega_l - \omega\right)^2 + \left(\nu_l + \gamma_l^{(f)}\right)^2} \quad (5.7a)$$

$$A \approx \frac{4\nu_l\gamma_l^{(f)}}{\left(\omega_l - \omega\right)^2 + \left(\nu_l + \gamma_l^{(f)}\right)^2} \quad (5.7b)$$

where ω_l is the frequency of the l -th plasmon mode; ν_l stands for dissipative damping; $\gamma_l^{(f)}$ is the radiative damping of the l -th plasmon mode, which can also be conceived

as the coupling coefficient between the plasmon modes and external excitation. When the thickness of the metal spacer layer h is much smaller than the skin depth of the metal, the condition $\gamma_l^{(f)} \ll \nu_l$ can be satisfied and strong coupling of the external excitation with the l -th plasmon mode will occur. At the vicinity of the l -th plasmon mode, $\omega_l - \omega$ approaches zero. From equations 5.7a and 5.7b, the transmittance approaches one and the absorbance approaches zero. It means that the excited plasmon modes in the dielectric nanorod interact with the point-dipole source strongly and the energy can be transmitted into the dielectric nanorod at high efficiency. The dissipative damping along the transmission channel is also minimized by keeping the metal spacer layer thin (the dissipative damping is proportional to h). Thus, in such a structure, high transmission can be achieved when the h is significantly thinner than the skin depth of the metal [93].

An immediate conclusion of the above analysis is that the single dielectric nanorod embedded in the metal interacts with a point-dipole source much stronger than the single metallic nanorod. For the investigated dielectric nanorod with a thin metal spacer layer, the transmission efficiency of the single dielectric nanorod at its resonance wavelength is much higher than that of the metallic nanorod. It implies that it might be possible to construct a dielectric nanorod waveguide for longer transmission distance.

5.2.3.3 Response of one metallic/dielectric nanorod chain to a point-dipole source

In this section, energy transportation along a metallic/dielectric nanorod chain for both longitudinal and transverse polarizations will be investigated. In the numerical simulations, the geometric parameters r , d and h are 20 nm, 23 nm and 3 nm, respectively. The metallic/dielectric nanorod chains are made of different number of

metallic/dielectric nanorods. The transmission spectra of the metallic/dielectric nanorod chains consisting of six metallic/dielectric nanorods are plotted in **Figure 5.7 (a) and (b)**. The simulation results clearly show that the metallic nanorod chain has a higher transmission under longitudinal polarization. In contrast, the dielectric nanorod chain has a higher transmission under transverse polarization. The higher transmission exhibited by the metallic nanorod chain under longitudinal polarization has been reported by several groups [61, 84, 89]. The shifting of the resonance wavelength from the individual metallic nanorod towards longer wavelength was also observed [61]. However, to the best of my knowledge, there is no report on the enhanced transmission by the dielectric nanorod chain under transverse polarization.

Figure 5.7 Transmission spectra of (a) metallic nanorod chain and (b) dielectric nanorod chain (consisting of six nanorods) under longitudinal and transverse polarizations.

In the following section, the nanocircuit model is used to quantitatively explain the high transmission phenomenon under appropriate polarizations in the two types of structures. To understand the excited plasmon modes around the transmission peaks, the charge distributions and electrical field intensity distributions in the dielectric nanorod chain under transverse polarization and that in the metallic nanorod chain under longitudinal polarization are plotted in **Figure 5.8 (a) and (b)**, respectively. The

first row in **Figure 5.8 (a)** and **(b)** illustrates the charge distributions and the second row shows the corresponding electrical field intensity distributions. It can be seen that the electrical field in both structures are confined around the interstitial sites along the chain axis (second row in **Figure 5.8 (a)** and **(b)**). Thus around the transmission peaks, the excited plasmon modes in both structures are bounded modes which can be used to guide the EM energy below the diffraction-limit.

Figure 5.8 Charge distributions (first row) and electrical field intensity distributions (second row) of the metallic/dielectric nanorod chains under longitudinal and transverse polarizations. (a) Metallic nanorod chain under longitudinal polarization. (b) Dielectric nanorod chain under transverse polarization.

To find the equivalent nanocircuit of the metallic/dielectric nanorod chains at their transmission peaks, we examine the charge distributions. The electrical field distributions in the metallic nanorod chain under longitudinal polarization are approximately dipole-like (**Figure 5.8 (a)**). For the dielectric nanorod chain under transverse polarization, the charge distributions are identical to that of the single dielectric nanorod illustrated in **Figure 5.5 (d)**. Based on the charge distributions, the equivalent nanocircuit model for both structures can be constructed. The nanocircuit

model for the metallic nanorod chain is identical to the nanocircuit illustrated in **Figure 5.3 (a)**. For the dielectric nanorod chain, however, we have to figure out the equivalent capacitance of the dielectric nanorod embedded in the metal with the corresponding charge distributions. Compared to the ideal dipole plasmon excitation in a dielectric nanorod embedded in the metal, the charge distribution in **Figure 5.8 (b)** resembles two parallel dipole excitations localized around the metal spacer layer. The equivalent circuit of the dielectric nanorod embedded in the metal with the electrical field distribution in **Figure 5.8 (b)** can be represented by two parallel connected capacitors. **Figure 5.9** shows the equivalent nanocircuit of an ideal dipole plasmon excitation and the parallel dipole excitations.

Figure 5.9 Equivalent nanocircuits of the dielectric nanorod embedded in metal under transverse polarization. (a) Equivalent nanocircuit of the parallel dipole excitations illustrated in Figure 5.5 (d). (b) Equivalent nanocircuit of an ideal dipole excitation.

The two parallel connected capacitors in the above figure can be combined, and eventually we can derive exactly the same nanocircuit as shown in **Figure 5.3 (a)**. By now, it is clear that the equivalent nanocircuits of both structures at their transmission peaks can be represented by the same right-handed transmission line circuit. Since the right-handed transmission line supports forward-wave mode propagations, it is not surprising that a high transmission can be obtained in both structures under appropriate polarizations. The role of the forward-wave mode in the transmission properties of the nanorod chain under longitudinal polarization has been confirmed by many groups [61,

89]. The magnetic field distributions along z -axis direction ($H//z$ -axis) at different times are plotted in **Figure 5.10** to visualize the propagation mode in the dielectric nanorod chain under transverse polarization. The figure clearly shows that the guided modes propagate in the forward direction as the time eclipses. This confirms that the results predicted by the nanocircuit model are sufficient to reveal the key properties for such kind of waveguide.

Figure 5.10 Visualization of the forward-wave propagation mode in the dielectric nanorod chain under transverse polarization. The time $\Delta t = 4.7685 \times 10^{-17}$ second.

The nanocircuits in **Figure 5.9** can also be used to explain the resonance wavelength of the dielectric nanorod under transverse polarization. Denoting the equivalent capacitance of the ideal dipole plasmon excitation as C_0 , the capacitance of the two parallel capacitors in **Figure 5.9 (a)** can be approximated by rC_0/t . The equivalent capacitance of the two parallel capacitors will be $2rC_0/t$. From the simple formula of an LC resonator

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (5.8)$$

It is clear that the increase of the capacitance will result in a decrease of the resonance frequency (or an increase in the resonance wavelength). This explains why the

resonance wavelength of the dielectric nanorod under transverse polarization becomes longer than 350 nm.

From the transmission spectra, it is also observed that the transmission efficiency of the dielectric nanorod chain under transverse polarization is much higher than that of the metallic nanorod chain under longitudinal polarization. As shown in **Figure 5.7**, the peak intensity for the dielectric nanorod chain and the metallic nanorod chain are 2.5×10^{-1} and 5×10^{-3} , respectively. This can be explained by employing equations 5.7a and 5.7b that were used to investigate the high transmission efficiency of the single dielectric nanorod embedded in the metal. The supported propagation mode in the dielectric nanorod chain is a forward mode; the energy transfer process can be described by a few steps. Firstly, the energy from the point-dipole source is coupled with the excited plasmon modes inside the first dielectric nanorod. Then the energy confined in the first dielectric nanorod is coupled with the excited surface modes inside the next dielectric nanorod. Finally, the energy is transferred to the end of the dielectric nanorod chain. In each of these steps, the transmittance and absorbance around the resonance wavelength can be approximated by equations 5.7a and 5.7b, respectively. This means that the excited plasmon modes in each individual dielectric nanorod are strongly coupled, and an energy transmission channel is formed along the chain. The near-field coupling mechanism plays the key role in the formation of the energy transmission channel. In addition to that, the transmission efficiency of the channel is also affected by the dissipative damping in the metal spacer layer. To achieve efficient energy transfer along the channel, the thickness of the metal spacer layer should be kept small as well. The above two conditions can be satisfied simultaneously by keeping the metal spacer layer significantly thinner than the skin depth of the metal. For the simulated structures, the metal spacer layer is 3 nm, which

is much smaller than the skin depth of the metal. Thus, high transmission can be achieved in such a dielectric nanorod chain.

5.2.3.4 Tuning the optical properties of the metallic/dielectric nanorod chains

One advantage of the metallic/dielectric nanorod chains is the flexibility in tuning their optical properties. In this section, The author presents how the optical properties of such waveguides can be tuned by varying their constituent materials or geometry.

Effect of the geometry parameters

The transmission spectra of the metallic/dielectric nanorod chains consisting of different number of metallic/dielectric nanorods are investigated. Since we are interested in waveguiding application, only the configurations that support forward-wave propagation modes are considered. In the simulations, the geometric parameters r , d and h are 20 nm, 23 nm and 3 nm, respectively. **Figure 5.11** shows the transmission spectra of the metallic/dielectric nanorod chains consisting of four, six and eight metallic/dielectric nanorods. It can be seen that, for the two types of structures, the transmission bandwidth decreases as the number of metallic/dielectric nanorods increases. The center positions of the transmission spectra for both structures only shift slightly as the number of the metallic/dielectric nanorods increases. This means that their transmissions are dominated by the fundamental modes. Some smaller peaks associated with propagation modes other than the fundamental one are also observed as the number of the metallic/dielectric nanorods increases. One important finding is that the damping rate in the metallic nanorod chain is much higher than that in the dielectric nanorod chain as the number of nanorod increases. As shown in

Figure 5.11 (a) and (b), the peak intensity in the metallic nanorod chain decreases from 13×10^{-2} to 0.16×10^{-2} as the number of nanorod increases from four to eight. In contrast, the peak intensity in the dielectric nanorod chain only decreases from 5 to 1.6. This again confirms that the dielectric nanorod chain has higher transmission efficiency when the metal spacer layer is thin.

Figure 5.11 Transmission spectra of (a) the metallic nanorod chains under longitudinal polarization, and (b) the dielectric nanorod chain under transverse polarization when the number of metallic/dielectric nanorod is increased.

Next, we investigate the effect of the diameter r on the transmission spectra. In the simulations, r is increased from 20 nm to 28 nm, while the remaining parameters are unchanged. The transmission spectra of the metallic/dielectric nanorod chains consisting of six metallic/dielectric nanorods are studied. As shown in **Figure 5.12**, the center wavelength of the dielectric nanorod chain shifts slightly towards the longer wavelength as the radius increases. This is because the capacitance is proportional to the diameter r , and a small increase in r will lead to an increase in its capacitance. From equation 5.8, an increase in the capacitance will cause the resonance frequency to decrease (or red-shift in the wavelength). In addition, it is found that the degree of damping in the dielectric nanorod chain is very small when the diameter is increased. As illustrated in **Figure 5.12 (b)**, the peak intensity of the dielectric nanorod chains

decreases slightly when the diameter is increased. In contrast, the peak intensity of the metallic nanorod chains decreases significantly when the diameter is increased. As stated earlier, material loss in such structures can be modeled as a nanoresistor connected in series with the nanoinductor. For the dielectric nanorod chain, the inductive element is the metal spacer layer. Since the metal spacer layer thickness ($h=3$ nm) is kept the same in all structures, the change in the nanoresistance is negligible. In contrast, the inductive element in the metallic nanorod chain is metal. An increase in the dimension of the metallic nanorod increases the corresponding nanoresistance, which increases damping. It can be seen that the major component that causes damping in the dielectric nanorod chain is the metal spacer layer, while the major component that causes damping in the metallic nanorod chain is the metal nanorod. In order to have a higher transmission, a smaller metal spacer is critical for the dielectric nanorods chain, while a smaller nanorod diameter is required for the metallic nanorod chain.

Figure 5.12 Transmission spectra of (a) the metallic nanorod chains under longitudinal polarization, and (b) the dielectric nanorod chains under transverse polarization when the diameter of the nanorod is increased.

The effect of the inter-nanorod spacing on the transmission spectra is investigated as well. In the simulations, the diameter of the metallic/dielectric nanorod is kept as 20

nm, while the inter-nanorod spacing is increased from 3 nm to 7 nm. **Figure 5.13** shows the transmission spectra of the metallic/dielectric nanorod chains consisting of six metallic/dielectric nanorods. It can be seen that the peak intensity for both structure decreases as h increases. The decrease in peak intensity can be explained from two aspects. Firstly, increasing h will decrease the strength of near-field coupling between the adjacent metallic/dielectric nanorods, which decreases the efficiency of energy interchange and thus the transmission. Secondly, for the dielectric nanorod chain, an increase in h will also increase dissipative damping, which will cause more decrease in the transmission. The blue shift of the transmission spectra in both structures can also be explained by the nanocircuit model. For the dielectric nanorod chain, an increase in h will result in an increase in the nanoinductance L , which causes a blue shift in the resonance wavelength. Similarly, for the metallic nanorod chain, the nanocapacitance increases as h increases. The increase in the nanocapacitance will also cause a blue shift in its resonance wavelength.

Figure 5.13 Transmission spectra of (a) the metallic nanorod chains under longitudinal polarization, and (b) the dielectric nanorod chains under transverse polarization when the inter-nanorod spacing d is increased.

Effect of dielectric materials

Based on the above analysis, it is not surprised that the transmission spectrum of both structures is red-shifted when the permittivity of the dielectric is increased. Since for the two types of structures, an increase in the dielectric permittivity corresponds to an increase in the nanocapacitance, it certainly increases the resonant wavelength. The transmission spectra of the metallic/dielectric nanorod chain consisting of six metallic/dielectric nanorods are illustrated in **Figure 5.14**. It can be seen that by changing the permittivity of the dielectrics, the resonant wavelength of both structures can be red-shifted over a wide range.

Figure 5.14 Transmission spectra of (a) the metallic nanorod chain under longitudinal polarization, and (b) the dielectric nanorod chain under transverse polarization when the permittivity of the dielectric is increased from 1.1 to 4.4.

5.2.4 Response of the dielectric nanorod chain to an unpolarized point source

In previous discussions, a point-dipole source with pure longitudinal and transverse polarizations was used as the excitation in order to have a clear understanding on the properties of the waveguides in response to different polarizations. To visualize the response of the metallic/dielectric nanorod chains on unpolarized point source, the transmission spectra of the two types of structures under an unpolarized point source are investigated. **Figure 5.15** shows the transmission

spectra of the metallic/dielectric nanorod chains consisting of six metallic/dielectric nanorods. Compared to the transmission spectra in **Figure 5.7** with specified polarization directions, the transmission spectra obtained in **Figure 5.15** shows little variations in terms of the spectrum shape and amplitude. Again, this indicates that the dominated modes in both structures are indeed the forward-wave propagation modes with the corresponding polarization directions. Thus, for unpolarized light source, only the components corresponding to the forward-wave propagation modes are transmitted along the two types of chains at high efficiency.

Figure 5.15 Transmission spectra of the metallic/dielectric nanorod chains consisting of six metallic/dielectric nanorods under an unpolarized point source. (a) metallic nanorod chain. (b) dielectric nanorod chain.

In summary, the guided forward-wave modes are supported by the metallic nanorod chain under longitudinal polarization and the dielectric nanorod chain under transverse polarization. The high transmission exhibited by the dielectric nanorod chain under transverse polarization is predicted and demonstrated. From fundamental physics, the energy transfer processes in such a chained structure can be explained from two aspects. Firstly, the strong near-field coupling between adjacent metallic/dielectric nanorod set up a transmission channel for energy transfer. Next, the transmission efficiency of the channel is determined by the dissipative damping

associated with the transmission channel itself. In order to achieve high transmission, strong near-field coupling and smaller damping are required. For the dielectric nanorod chain, both conditions can be satisfied when the metal spacer layer is kept smaller than the skin depth and much higher transmission can be achieved.

5.3 Applications of the metallic/dielectric nanorod chain for imaging

From the above analysis, it is clear that both the metallic nanorod chain and dielectric nanorod chain can be used for guiding of the EM wave in the scale comparable to their feature size. Their confinement abilities make them possible as a lens in a form of a two-dimensional array. In such a lens, the sub-wavelength information emitted from an object can be guided and transferred along the channels that are formed by the metallic/dielectric nanorod chains. The final limit on the resolution of the lens would be the granularity of the transmission channels. The degree of cross-talk between the adjacent transmission channels is the determining factor that affects the resolution of the lens. In order to achieve a higher resolution, the cross-talk among imaging channels should be well controlled. For many of previously proposed metamaterial lenses such as the metal nanorod lenses and the metallic nanolenses, their image transmission channels are separated by the lossless dielectrics [29, 30]. The guided surface waves on their transmission channels extend some distance away and interfere with adjacent channels. Although the cross-talk can be reduced by optimizing the design, the degree of improvement on the resolution is rather limited. Based on the waveguiding properties of the dielectric nanorod chain, such problems can be solved by using the dielectric nanorod chain. Compared with its complementary structures, the dielectric nanorod chain offers two unique advantages. Firstly, it gives better confinement, since most of the EM energy is confined inside the

dielectric nanorod. Secondly, as the adjacent transmission channels are separated by the lossy metallic layers, the guided surface waves are essentially damped before they reach the adjacent transmission channels. These two unique features of the dielectric nanorod chains make it possible to achieve a resolution better than the lens constructed by its complementary structure.

5.3.2 Resolution of the metallic/dielectric nanorod chain lens

As discussed in the beginning of this section, the cross-talk among transmission channels is the determining factor that affects the final resolution of the lens. Thus, in addition to the higher transmission, the cross-talk should also be taken into account for the overall imaging performance. For a pixel-to-pixel lens constructed by an array of dielectric nanorods chains with the geometries illustrated in **Figure 5.16**, the optimized working wavelengths with minimized cross-talk is investigated numerically. To make the simulations more realistic, a 20 nm wide slit opened on a Cr mask layer is used as the diffraction-limited object, and a TM polarized plane wave is normally illuminated onto the slit (**Figure 5.16 (b)**). The time averaged power flow ($S=1/2*\text{Re}(E \times H^*)$) which accounts both the EM energy is used to qualify the intensity of the image. The cross-talk between the adjacent channels is qualitatively evaluated by measuring the PSF of the image at the output surface. The geometry parameters of the simulated lenses are $r=20$ nm, $w=50$ nm, and $d=23$ nm.

Figure 5.16 Schematic of the lens made of dielectric nanorod chains. (a) Three-dimensional view. (b) Cross sectional view. The width of the slot opened on the Cr mask layer is 20 nm.

The degree of cross-talk among transmission channels are determined by the strength of the LSPs coupling along the x -axis and the y -axis. By creating a strong anisotropy along the x -axis and the y -axis, the effective dielectric constants will inevitably result in different LSPs eigenmodes with their corresponding dispersion relations along the x -axis and the y -axis, thus creating optical anisotropy for LSPs fields. The constructed metamaterial can be considered as an anisotropic metamaterial. It is possible to ensure that only the LSPs eigenmodes along the y -axis are excited while the LSPs eigenmodes along the x -axis are suppressed.

The proposed metallic/dielectric nanorod chain lens as illustrated in **Figure 5.16** can be considered as an anisotropic plasmonic metamaterial. The degree of anisotropy that can be achieved by such metamaterials is a function of the geometric parameters (diameter, inter hole distances). Apply the EMT, the three diagonal elements of the dielectric nanorod chain lens can be approximately expressed by

$$\epsilon_{eff} = \frac{\epsilon_m \left[(L-1)(s-1)\epsilon_m + (L+s-Ls)\epsilon_d \right]}{(1+sL-L)\epsilon_m + L(1-s)\epsilon_d} \quad (5.8)$$

where s the filling factor of the structure, defined by the volume ratio occupied by the dielectric nanorod inclusion; L is a factor related to the shape of the inclusion, and it is 0.5 for cylindrical nanorods. For the case of metallic nanorod chain lens, the effective

permittivities can be derived by inter-changing ϵ_m and ϵ_d . **Figure 5.17** shows the degree of anisotropy for the proposed dielectric nanorod chain lens, in which the anisotropy is defined as the ratio of the effective permittivities along the x -axis and y -axis direction. It can be seen that strong anisotropy can be achieved around 560 nm, which is in good agreement with the numerical simulations shown in the next paragraph. To make a comparison, the anisotropy that can be achieved by the metallic nanorod chain lens is also plotted in the figure. The red dotted line shows the anisotropy that can be achieved by the metallic nanorod chain lens with the same geometry as the dielectric nanorod chain lens. The blue dashed line shows the strongest anisotropy that can be achieved by the metallic nanorod chain lens with an optimized metal spacer layer of 10 nm thick. It can be seen that, the dielectric nanorod chain lens is superior to the metallic nanorod chain lens in achieving strong anisotropy.

Figure 5.17 The degree of anisotropy that can be achieved by the metallic/dielectric nanorod chain lens. Black solid line: dielectric nanorod chain lens with the thickness of the metal spacer $h=3$ nm. The blue dashed line and red dotted line are the metallic nanorod chain lens with the thickness of the metal spacer $h=10$ nm, and $h=3$ nm, respectively.

For the dielectric nanorod chain lens shown in **Figure 5.16 (b)**, the minimum cross-talk can be achieved around $\lambda=560$ nm, and it is independent of the number of the dielectric nanorods. To visualize the degree of cross-talk for the lenses made of

dielectric nanorod chains. **Figure 5.18** shows the energy flow distributions and the corresponding PSF of the image at the output surface of the lenses made of different number of dielectric nanorods for the incident wavelength of 560 nm. From **Figure 5.18 (a)-(d)**, it is seen that the light from the slit is not only coupled to the dielectric nanorod directly beneath it but also to other dielectric nanorods. However, as the energy coupled to other dielectric nanorods is far less and decreases significantly with the increasing distance from the source, the image is primarily contributed by the EM energy in the dielectric nanorod beneath the slit.

It is also seen that the FWHMs of the field intensities at the output surfaces are less than 16 nm, which is smaller than the diameter of the dielectric nanorods, indicating suppressed spreading at output surfaces. At the input side, the impinging light strongly interacts with the first dielectric nanorod beneath the slit and excites the LSPs in it. Due to the small diameter and negative curvature of the dielectric nanorod, the excited surface plasmon modes are essentially confined on a scale comparable to the diameter of the dielectric nanorods. At the output surface, when the energy is decoupled from the last dielectric nanorod, due to the momentum mismatch between the wave vector of the LSPs in the dielectric nanorod and that required to excite SPPs at the silver surface, only a negligible amount of energy is converted into propagating SPPs along the silver surface. Thus, the image spreading at the output surface can also be suppressed. The above analysis showed clearly that the strength of the anisotropy plays a critical role in controlling the cross-talk among the transmission channels, by creating a strong anisotropy, it is possible to decrease the separation of the transmission channels to a distance that much smaller than the wavelength, enable deep sub-wavelength imaging.

Figure 5.18 Energy flow distributions and the corresponding PSF at the output surface of the lenses made of (a) two dielectric nanorods, (b) four dielectric nanorods, (c) six dielectric nanorods, and (d) ten dielectric nanorods. The wavelength of the plane wave is 560 nm.

For comparison, lenses made of metallic nanorod chains with the same geometry parameters were also simulated. It is found that the cross-talk among metallic nanorod chains is very strong over the entire visible spectrum and the cross-talk increases as the number of the nanorod increases. The waveguiding properties are completely different from those of a single metallic nanorod chain. For lenses made of more than two metallic nanorods, due to the strong coupling among the transmission channels, it is nearly impossible to use them as imaging lens. The energy flow distributions for lenses made of two row and four row metallic nanorods are plotted in **Figure 5.19** at the wavelength which has minimum cross-talk in the lenses. It can be seen that the cross-talk is too strong to see the image.

Figure 5.19 The energy flow distributions of the lenses made of made of two row and four row metallic nanorods.

The imaging capability of the dielectric nanorod chain lens is evaluated by two 50 nm-spaced point sources. The wavelength of the point sources is maintained as 560 nm. **Figures 5.20 (a)** and **Figures 5.20 (b)** shows the energy flow distribution and intensity of two 50 nm-spaced slits at the output surfaces of the lens, respectively. Clearly, most of the light from the two slits is guided along the two dielectric nanorod chains (A and B) beneath them although a small and negligible portion of the light is coupled to the adjacent dielectric nanorod chains.

Figure 5.20 Energy flow distributions and the corresponding intensities at the output surface of the lenses made of six dielectric nanorods when two 50 nm-spaced slits are imaged. (a) The energy flow distributions inside the lens, and (b) the intensity at output surface of the lens when two 50 nm-spaced slits are being imaged.

5.3.3 Imaging with a longer transmission distance

In the previous discussion, the dielectric nanorod chain lenses are made of only six dielectric nanorods. The image can be transferred to a longer distance by employing more dielectric nanorods. As shown in **Figure 5.21**, the lens is made of twenty rows of dielectric nanorods with a total thickness of 463 nm. From the figure, the two 50 nm-spaced slits can be clearly resolved by the lens made of 20 dielectric nanorods.

Figure 5.21 Imaging of two 50 nm-spaced slits with a lens made of twenty dielectric nanorods. (a) The energy flow distribution inside the lens. (b) The energy distribution at the output surface of the lens.

5.3.4 Limitations of the dielectric nanorod chain lens

The major limitation of the dielectric nanorod chain lens is that its imaging performance strongly depends on the geometric parameters. The thickness h of the metal spacer layer plays a very important role in determining the transmission, as well as the resolution of the lens. The metal spacer layer has to be much thinner than the skin depth of the metal in order to achieve a high transmission and strong anisotropy. A small variation in the geometry or a defect may lead to a significant change in the imaging performance. As the thickness of the metal spacer layer is smaller than 10 nm,

it is difficult to be realized by current nanofabrication techniques. Thus, the realization of such lenses is primarily limited by the nanofabrication techniques.

Despite the difficulties in realization of the dielectric nanorod chain lens, such kind design provides an entirely new way to construct a metamaterial lens, which uses the dielectric as the major medium for image transfer, rather than the lossy metals that used by current designs.

5.4 Summary

This chapter deals with the waveguiding properties of the closely-spaced dielectric nanorod chain and its application for sub-wavelength imaging. A nano-scale waveguide made of closely-spaced dielectric nanorod chain is proposed, and its performance is compared with the metallic nanorod chain. It is found that the dielectric nanorod chain has higher transmission efficiency under transverse polarization, in contrast to the metallic nanorod chains under longitudinal polarization. It is found that the energy transfer in the two types of structures by a right-handed transmission line which supports forward-wave propagation. The forward-wave propagation in dielectric nanorod chain is numerically demonstrated. It is also found that the dielectric nanorod chain exhibits a strong light-matter interaction and a much higher transmission can be achieved when the metal spacers between two adjacent dielectric nanorods are kept small.

In section 5.3, a plasmonic metamaterial lens made of dielectric nanorod chains is proposed. The performance of metamaterial lenses with the metal as the main transmission medium is primarily affected by image spreading at the input surface, cross-talk among transmission channels, and the inherent loss. The dielectric nanorod chain lenses that proposed here can significantly improve the lens performance. In the

lens, the image spreading problem at the input surface can be addressed by exciting the LSPs inside the dielectric nanorod rather than at the input surface. Upon near-field interactions, the LSPs then set up coupled plasmon modes, leading to the coherent propagation of energy along the dielectric nanorod chain with high confinement. The metal that used to separate the dielectric nanorod chains can effectively suppress the cross-talk among chains. Because of these, the dielectric nanorod lens is capable of high resolution and a long transmission distance.

Chapter 6. Unidirectional SPPs excitation and its application for imaging

This chapter is divided into two parts. In the first part, a new scheme on unidirectional SPPs excitation is proposed and theoretically demonstrated. In the second part, the application of such unidirectional SPPs generators for sub-wavelength imaging is investigated, and a planar magnifying lens is proposed. Section 6.1 gives an introduction. Several major issues associated with current unidirectional SPPs excitation devices will be discussed. Section 6.2 presents a new scheme on unidirectional SPPs excitation. In section 6.3, a planar magnifying lens made of such unidirectional SPPs generators is discussed.

6.1 Introduction

SPPs offer the unique opportunity to realize several groundbreaking applications such as sensing, imaging and optical integration. The ultimate confinement capability of SPPs makes it one of the most promising technologies to bridge the gap between nano-electronic and micro-photonics. Over the past decades, many functional plasmonic devices such as waveguide [226], beam couplers [227], and splitters [228, 229] have been proposed.

One of the key components in plasmonic devices is the SPPs generator which is used to launch SPPs beams at MD interfaces. SPPs beams are usually launched by a diffractive grating or a narrow slit. Although the coupling efficiency of a slit is lower than that of a diffractive grating, the slit structure has its own advantages. Despite its compact size, the slit structure requires little design and is very simple to implement. A slit can couple with light of different frequencies, which means that it can be

modeled as a collection of SPPs sources containing the required wave vectors to excite SPPs at MD interfaces. Under normal incidence, such symmetric structures generate two propagating SPPs beams along the MD interfaces, with equal amplitude but opposite directions [230]. In order to make use of the full potential of SPPs, it is desirable to excite SPPs only in one direction. This kind of SPPs excitation is also named as unidirectional SPPs excitation. For the diffractive grating and slit, the amount of scattered wave vectors propagating into both the positive and negative directions are the same under normal incidence. Thus, propagating SPPs beams are generated at both sides with an equal degree of excitation. To achieve SPPs excitation in one direction, the symmetry of either the incident light or the geometry of the structure has to be broken. The simplest way to achieve unidirectional SPPs excitation is to apply an oblique incidence [231-233]. However, in many cases, due to the complexity of the optical system, oblique incidence may not be an option. Many other schemes on unidirectional excitation of SPPs were proposed. One of the common methods to achieve unidirectional SPPs excitation is to introduce asymmetry to the structure. For example, unidirectional SPPs excitation can be achieved under normal incidence by breaking the symmetry of the single slit or grating [234-239]. Structures consist of two parallel slits filled with different dielectrics have shown capable of unidirectional SPPs excitation [231, 240]. A variety of other schemes has also been proposed for unidirectional launching of SPPs [233, 238, 241, 242]. These previous works have greatly accelerated the development of functional plasmonic devices. However, as many of these structures rely on interference of two different SPPs sources generated by additional periodical structures or cavities, device dimension becomes one of the obstacles that limit the practical implementation of such structures. So far, the most compact scheme for unidirectional SPPs excitation is the asymmetric

single nanoslit with a lateral dimension of 370 nm [233]. Compared with the current nano-electronic devices, the size of such SPPs generators is too large for device integration.

The unique advantage offered by plasmonic devices over traditional photonic devices is the capability to manipulate light in a scale beyond the diffraction-limit, and this cannot be accomplished if the size of the plasmonic devices itself is too large. Hence, it is desirable to design more compact SPPs generators with unidirectional SPPs excitation capabilities. In addition, as most of the current schemes on unidirectional SPPs excitation take the incident angle as one of the input parameters, the performance of the device is incident angle dependent. In real applications, the incident angle may not always be fixed in the normal direction. Thus, a good SPPs generator should also avoid the dependence on the incident angle. Despite the size and incident angle, the diffraction grating-based scheme for unidirectional excitation of SPPs usually relies on the incident frequency, the working spectrum of these devices is rather limited [243]. A good SPPs generator should not only be capable of efficient unidirectional launching of SPPs, but also have a broad working spectrum.

To address these issues, in the first part of this chapter, a new scheme for efficient unidirectional SPPs excitation with backside illumination is proposed. The proposed structure has a feature size of nanometer scale, works over a broad spectrum and at nearly arbitrary incidence angle and can be fabricated with a high level of tolerance to defects.

6.2 A new scheme for unidirectional SPPs excitation

6.2.1 Structure and mechanism

In this section, the structure and mechanism of the proposed scheme for unidirectional SPPs excitation are presented. As illustrated in **Figure 6.1 (a)**, the proposed structure consists of a thin metal layer "B" covered by another metal mask layer "A" on which a partially filled slot is opened. The two metal layers "A" and "B" can be made of the same material, and here Ag and Cr are used for demonstration, as illustrated in **Figure 6.1 (b)**. The substrate and ambient are modeled as the high-index dielectric and air, respectively. When a TM polarized plane wave is illuminated on the slot, unidirectional SPPs excitation can be achieved at the silver/substrate interface beneath the dielectric inclusion.

Based on the functionality of each component, the structure can be divided into two functional blocks: The first block resembles a partially filled MDM slot structure (Block 1 in **Figure 6.1 (a)**). Its primary function is to control the SPPs propagation direction. In such a partially filled MDM slot, the energy distribution inside the low-index (air) and high-index (dielectric) regions can be easily manipulated by controlling the contrast of the refractive indices of the two materials. When the contrast of the refractive indices is high enough, most of the energy is confined in the air region. The second block is the thin Ag layer located beneath the MDM slot (Block 2 in **Figure 6.1 (a)**). It controls the strength of the SPPs excited at the air/Ag and dielectric/Ag interfaces, as illustrated in **Figure 6.1 (b)**. From fundamental physics, the strength of the excited SPPs at any metal/dielectric interface can be deduced by studying their dispersion relations. For the proposed structure shown in **Figure 6.1 (b)**, since two combinations of metal/dielectric interfaces (air/Ag and dielectric/Ag) are employed, it should be possible to achieve strong SPPs excitation at the dielectric/Ag interface

while weak SPPs excitation at the air/Ag interface by selecting a proper incident wavelength. When the two functional blocks are combined together, the energy confined inside the air region can effectively couple with the SPPs excited at the dielectric/Ag interface. Due to the asymmetric arrangement of the air region and the dielectric region (the air region is located on the left side of the dielectric region), for the wave components in the air region, only these with wave vectors pointing to the positive x -axis direction can couple with the SPPs excited at the dielectric/Ag interface. Thus the SPPs excited at the dielectric/Ag interface will have a preferential propagation direction toward the positive x -axis. Next, when the EM energy confined at dielectric/Ag interface is coupled to the output surface, the excited SPPs at output surface preserve the same propagation direction.

Figure 6.1 Schematic illustration of the scheme for unidirectional SPPs excitation. (a) Structure and principle of the proposed scheme. (b) Structure and materials used for numerical simulations.

The idea is schematically illustrated in **Figure 6.1(b)**. When a plane wave is illuminated on the slot, the incident wave is scattered by the slot and high spatial frequency components with $k_{x_incident} \gg k_0$ are generated, where $k_{x_incident}$ and k_0 are the transverse wave vector of the scattered wave and the free space wave vector,

respectively. Due to the high refractive index contrast between the air and high-index dielectric, the scattered waves are mainly confined in the air region and they contain transverse wave components pointing to both positive x -axis and negative x -axis directions. Since the high-index region is located at the right side of the air region, for the scattered waves confined in the air region, only these waves with the transverse wave vector pointing to positive x -axis can reach the dielectric/Ag interface. If these wave components can provide sufficient transverse wave vectors to excite SPPs at the dielectric/Ag interface, the excited SPPs will have a propagation direction along the positive x -axis. Next, when the SPPs excited the dielectric/Ag interface is coupled with the plasmon modes excited at the output surface, the excited SPPs also propagate along the positive x -axis direction. As the scheme only relies on the geometric manipulation of the energy distribution to control the SPPs excitation direction, the slot can be scaled down to an extremely small size and work with arbitrary incidence angle.

6.2.2 Theoretical analysis and numerical simulations

Numerical simulations of the proposed structure are performed to demonstrate the idea. In the simulations, the dimensions of the structure are maintained the same as that shown in **Figure 6.1 (b)**. The width of the slot is 50 nm, and it is half filled with a high-index dielectric with a permittivity of 4. In the optical range, such a high-index dielectric permittivity can be realized by a variety of materials such as Silicon nitride (Si_3N_4), Zinc oxide (ZnO) and Titanium dioxide (TiO_2). At 515 nm, the permittivities of the above mentioned materials are 4.123 [244], 4.16 [245] and 7.2 [246], respectively. The permittivities of Ag and Cr are extracted from experimental data [120]. The dimension of the simulation domain is 3000 nm $\times$ 8000 nm, and all the

boundaries are set to PMLs to reduce the back scattered waves. The maximum mesh size of the whole structure is 2 nm, and it is decreased to 0.2 nm for regions around the silver slab and slot to improve the accuracy. When a TM polarized plane wave ($\lambda=515$) is normally illuminated on the slot, simulation results show that high efficient unidirectional SPPs excitation can be achieved at the output surface. The energy flow distribution (named as the power flow distribution in COMSOL 3.5a) and magnetic field distribution inside the structure are plotted in **Figures 6.2 (a) and (b)**, respectively. They clearly show that the majority of the energy is directed to the right side of the slot at the output surface. The results become clearer by qualitatively measuring the SPPs beam intensity at the output surface, as shown in **Figure 6.2 (c)**. The normalized intensity in the figure is obtained by scaling the actual intensity with respective to the maximum intensity. From the simulations results, it is convinced that the proposed scheme can be used for unidirectional SPPs excitation.

Figure 6.2 Unidirectional SPPs excitation by the proposed structure at $\lambda=515$ nm. (a) Energy flow distribution inside the structure. The inset of the figure illustrates the energy distribution around the slot with better contrast. (b) Magnetic field distributions. (c) SPPs beam intensity distributions at the output surface (silver/substrate interface) of the structure.

The mechanism of the unidirectional SPPs excitation in the proposed structure can be understood by investigating the energy distributions inside the partially filled

MDM slot. The introduction of the high-index dielectric will modify the local energy distribution inside the slot from two aspects. Firstly, the discontinuity in the refractive index caused by the dielectric inclusion breaks the symmetric energy distribution inside the slot, resulting in unequal amount of energy being distributed in each region. The MDM slot structure has been investigated by many research groups. In such kind of structure, the electric field polarized perpendicular to the air/Cr interface is bounded around the interfaces due to the high dielectric discontinuity between air and Cr. When the two interfaces of the Cr slot are brought closer each other, the plasmonic waves around the two interfaces interact and the light is almost completely confined inside the air slot [248, 249]. From energy confinement point of view, the fundamental odd mode of such a MDM slot does not exhibit a cut-off for vanishing slot width [61], thus it is possible to decrease the slot to an extremely small size without the concern of altering its energy distribution profile. **Figure 6.3 (a)** shows the energy distribution of a 50 nm wide MDM slot when there is no dielectric inclusion. It can be seen that, majority of the energy is confined inside the slot region. The energy flow distribution profile along the cutline in **Figure 6.3 (a)** is plotted when the width of the slot is varied from 30 nm to 70 nm. From **Figure 6.3 (b)**, it can be seen that although the total amount of energy decreases as the slot width decreases, the energy is well confined inside the slot region.

Figure 6.3 Effect of slot width on the energy distribution inside the MDM slots. (a) Energy distribution inside the slot ($w=50$) when a 515 nm TM polarized plane wave is normally illuminated. (b) Energy distributions measured at the cutline located at the plane 30 nm from the bottom of the slot.

Next, when a high-index dielectric is added, the dielectric discontinuity at the dielectric/air interface breaks the symmetrical energy distribution inside the MDM slot. By applying the continuity of the electric displacement vector D at the dielectric/air interface, it is easy to show that the normal component of the electric field E_x in the air region is increased by a factor of ϵ_d , where ϵ_d is the permittivity of the dielectric inclusion. Since the slot width is smaller than the decay length of the fundamental mode of the MDM slot, the electric field normal to the dielectric/air interface remains high across the air region. Thus the energy distribution in the air region can be much higher than that in the high-index dielectric region. **Figure 6.4 (a)** illustrates the energy flow distribution profile inside the partially filled MDM slot. It clearly shows that more energy is confined in the air region before it couples with the excited SPPs at the silver/dielectric interface. The intensity is qualitatively evaluated in **Figure 6.4 (b)**. To reduce the amount of the energy contributed by the excited SPPs at the silver/dielectric interface, the light intensity is measured at the plane 30 nm from the bottom of the slot. Simulations also reveal that the higher is the contrast ratio between

the dielectric and air, the more the energy confined inside the air region. Similar results have been found for dielectric slot-waveguide made of high-index-contrast materials [251]. Since more energy is confined in the air region which is located on the left side of the dielectric/Ag interface, when the energy is coupled with SPPs excited at dielectric/Ag interface, most of the excited SPPs will have wave vector components pointing to the positive x -axis. In this way, the propagation direction of the excited SPPs can be controlled. From the simulation results, it can be seen that more than half of the energy can be confined in the air region as long as the permittivity of the dielectric included is larger than 4. For realistic materials, this can be achieved by high-index dielectrics such as silicon nitride (Si_3N_4) and zinc sulfide (ZnS).

Figure 6.4 Effect of the permittivity of the high-index dielectric included on the energy distribution profile inside the MDM slot. (a) Energy distribution inside the partially filled slot ($\epsilon_d=4$). (b) Energy distributions measured at the cutline located at the plane 30 nm from the bottom of the slot when the permittivity of the high-index dielectric is varied.

In addition to the lateral energy distribution, introducing a high-index dielectric into the slot will also affect the strength of the SPPs excited at the air/Ag and dielectric/Ag interfaces. Because the light line is located on the left side of the SPPs dispersion relation, many of the previously researches on SPPs are limited on exploring functional plasmonic devices by incidents with small transverse wave

components. However, if we look at the SPPs dispersion curve, it is also possible to create some novel functional devices if the incidence primarily consists of large transverse wave components. In this work, unlike traditional methods which focused on SPPs excitation by incidence with small transverse wave components, incidence with large transverse wave components is used to achieve the desired SPPs excitation. For simplicity, we first show the idea by considering the dispersion relations of the propagating SPPs at a MD interface [61]

$$k_{spp} = k_0 \sqrt{\frac{\epsilon_{metal} \epsilon_{dielectric}}{\epsilon_{dielectric} + \epsilon_{metal}}} \quad (6.1)$$

where k_0 is the free space wave vector, ϵ_{metal} and $\epsilon_{dielectric}$ are the permittivities of metal and dielectric, respectively. Considering the case $Re(\epsilon_{metal}) < 0$, $|Re(\epsilon_{metal})| > \epsilon_{dielectric}$ and $Re(\epsilon_{metal}) \gg Im(\epsilon_{metal})$, the SPPs dispersion relation at the air/Ag and dielectric/Ag interfaces can be approximated by the following equations.

For the air/Ag interface:

$$k_{spp_air} \approx k_0 \sqrt{\frac{Re(\epsilon_{Ag})}{(1 + \epsilon'_{Ag})}} + k_0^3 \sqrt{\frac{Re(\epsilon_{Ag})}{(1 + \epsilon'_{Ag})}} \frac{Im(\epsilon_{Ag})}{2(\epsilon'_{Ag})^2} i \quad (6.2)$$

For the dielectric/Ag interface:

$$k_{spp_dielectric} \approx k_0 \sqrt{\frac{Re(\epsilon_{Ag}) \epsilon_d}{(\epsilon_d + Re(\epsilon_{Ag}))}} + k_0^3 \sqrt{\frac{\epsilon_d Re(\epsilon_{Ag})}{(\epsilon_d + Re(\epsilon_{Ag}))}} \frac{Im(\epsilon_{Ag})}{2(Re(\epsilon_{Ag}))^2} i \quad (6.3)$$

where $Re(\epsilon_{Ag})$ and $Im(\epsilon_{Ag})$ are the real part and imaginary part of the permittivity of silver, ϵ_d is the permittivity of the dielectric inclusion and i is the imaginary number.

Figure 6.5 plots the dispersion relations of the SPPs propagating at the air/Ag and the dielectric/Ag interfaces for $\epsilon_d=4$. It can be seen that from the dispersion relations, over a broad spectrum (above 380 nm), the wave vector $k_{spp_dielectric}$ required to excite SPPs at the dielectric/Ag interface is always higher than the wave vector k_{spp_air} required to

excite SPPs at the air/Ag interface. Assuming incidents with extremely large transverse wave components are used to excite SPPs at both interfaces, due to the smaller wave vector mismatch, the SPPs excited at dielectric/Ag interface will be much stronger than that excited at the air/Ag interface.

By studying the SPPs dispersion relations, it is evident that, for incidence with sufficient large transverse wave components, such a structure can be configured as a device to selectively excite SPPs at the dielectric/Ag or air/Ag interfaces by tuning the working wavelength. As the proposed scheme uses a slot with a dimension much smaller than the wavelength, these extremely large transverse wave components can be simply generated by the scattered light at the partially filled MDM slot in block 1. To quantitatively estimate the phase mismatches between the scattered light and both SPPs, we estimated the dominant transverse wave vector components of the scattered light. The spectrum of the dominant wave vector components of $k_{x_incident}$ is plotted in **Figure 6.5(a)**. It can be seen that the scattered light indeed contain high transverse wave vector components larger than both $k_{spp_dielectric}$ and k_{spp_air} . For $\lambda > 380$ nm, the wave vector mismatch between $k_{x_incident}$ and $k_{spp_dielectric}$ is smaller than that between $k_{x_incident}$ and k_{spp_air} . Thus the strength of the SPPs excited at the dielectric/Ag interface can be much stronger than that excited at the air/Ag interface.

Figure 6.5 Dispersion relation of SPPs at the interfaces between air/Ag (blue dashed curve) and dielectric/Ag (black solid curve). (a) The horizontal axis and the vertical axis correspond to the real part of the wave vector and wavelength, respectively. (b) The horizontal axis and the vertical axis correspond to the imaginary part of the wave vector and wavelength, respectively.

In the previous paragraph, for simplicity, we only considered the SPPs on single dielectric/Ag or dielectric/Ag interface. For the proposed structure, the SPPs at the two interfaces of the Ag layer couple with each other and give rise to coupled plasmon modes due to the finite thickness of the Ag layer. The SPPs that should be considered are the SPP modes supported by the MDM structures discussed in Chapter 2 [252]. The SPPs dispersion relation of such MDM structures can be evaluated by the following equation [61]

$$e^{-2k_1 a} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2} \cdot \frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3}. \quad (6.4)$$

where k_1 and ε_1 are the wave vector and permittivity of the metal layer, k_2 and ε_2 , k_3 and ε_3 are the wave vectors and permittivities of the two insulator layers, respectively. In order to show that similar results can be achieved when the SPPs supported by dielectric/Ag/dielectric and air/Ag/dielectric layers are considered, the dispersion curves of the dielectric/Ag/dielectric and air/Ag/dielectric layers are plotted in **Figure 6.6**. As shown in the figure, the dispersion relation of the dielectric/Ag/dielectric

layers splits into even and odd modes. For $\lambda > 360$ nm, the dispersion curves of the dielectric/Ag/dielectric layers are located on the right hand side of that of the air/Ag/dielectric layers. Due to the smaller momentum mismatch, the dominant transverse wave vector components of the scattered light will couple with either the even or odd SPP modes of the dielectric/Ag/dielectric. In this spectrum range, the strength of the SPPs excited at the dielectric/Ag/dielectric layers can be much stronger than that excited at the air/Ag/dielectric layers. It is also found that the even mode of the dielectric/Ag/dielectric layers intersects with the dominant transverse wave vectors of the scattered light at 400 nm (intersect 1) and 510 nm (intersect 3), respectively. At these two intersecting points, the dominant incident wave vectors are perfectly matched with that required to excite the SPPs at the dielectric/Ag/dielectric layers, and thus high efficient excitation of SPPs should be achieved. While for $\lambda \approx 340$ nm, the momentum mismatch between the incident wave vectors and that of required to excite SPPs at the air/Ag/dielectric layers becomes smaller. Thus high efficient excitation of SPPs at the air/Ag/dielectric layers should be achieved around 340 nm.

Figure 6.6 Dispersion relation of SPPs at the air/Ag/dielectric layers (blue dashed curve) and the dielectric/Ag/dielectric layers (even mode: red solid curve, odd mode: black dotted curve), and the spectrum of the dominant transverse wave vector components of the scattered light (violet scatter plot).

Next, numerical simulations are carried out to qualitatively evaluate the above theoretical analysis based on the dispersion relations. The strength of the SPPs excited at each interface is numerically evaluated by measuring the energy confined at each interface. In the numerical simulations, the SPPs beam intensity is used to qualify the EM energy. The energy confinement is evaluated by taking the integral of the intensity at each interface. **Figure 6.7** shows the energy confined at each interface when the wavelength is varied from 320 nm to 800 nm. At the air/Ag interface, the maximum intensity is achieved around $\lambda=350$ nm (peak 2), which is in good agreement with the theoretical value predicted by the dispersion relation. At the dielectric/Ag interface, two peaks are observed. From the dispersion curves in **Figure 6.6**, they correspond to the two intersecting points 1 and 3, respectively. Based on the above discussions, it is clear that the strength of the SPPs beams at the dielectric/Ag interface can be much stronger than that of the air/Ag interface.

Figure 6.7 Strength of SPPs excited at the dielectric/Ag and air/Ag interfaces of the slot with a width of 50 nm. Peak 1, 2 and 3 are centered at 410 nm, 350 nm and 515 nm, respectively.

Although the numerical simulation results in **Figure 6.7** indicate that strong excitation of SPPs at the dielectric/Ag interface can be achieved at both peaks centered at 410 nm and 515 nm, only the spectrum around 515 nm is suitable for unidirectional

SPPs excitation. In order to obtain SPPs with long propagation distance at the output, the imaginary part of $k_{spp_dielectric}$ should be as small as possible. Since the dielectric included and substrate are made of the same material, they share the same SPPs dispersion relation. Referring to the imaginary part of the SPPs dispersion relation at the dielectric/Ag interface in **Figure 6.5 (b)**, it is obvious that the imaginary part of the wave vector around peak 1 is very large. It means that peak 1 corresponds to the strong resonance condition ($\lambda=410$ nm), and it is associated with huge losses. However, the condition for peak 3 is different. As shown in **Figure 6.5 (b)**, the imaginary part of the wave vector around 515 nm is about 0.08 which is about 2% of that around 410 nm. Therefore, the incidence at around 515 nm should have a much longer propagation distance, which can be found in **Figure 6.2**.

6.2.3 Performance evaluation

To qualitatively evaluate the unidirectional SPPs excitation efficiency of the structure, a ratio is defined as

$$\eta = \frac{I_R}{I_R + I_L} \quad (6.5)$$

where I_R and I_L are the intensity of the SPPs beams transported to the right hand side and left hand side of the dielectric slot at the output surface. We take the I_R and I_L at 500 nm and -500 nm from the center of the slot, respectively. As illustrated in **Figure 6.1 (b)**, the ratio η is as high as 93% at $\lambda=515$ nm. These results undoubtedly indicated that most energy propagate in the positive x -axis direction.

6.2.3.1 Variation in incident wavelength

In this section, the effect of incident wavelength on the performance of the unidirectional SPPs generator is investigated. It is well known that one major

advantage of the slot structure is that it can couple with light of different frequencies. The partially filled MDM slot structure also exhibits similar properties and has a broad working spectrum. In addition, as it can be seen from the SPPs dispersion relations in **Figure 6.6**, as long as the incident wavelength is above 340 nm, the strength of the SPPs excited at the dielectric/Ag interface is stronger than that at the air/Ag interface. This means that as long as the incident wavelength is above 340 nm, unidirectional SPPs excitation can be achieved by the proposed structure. To numerically evaluate the performance of the structure when the incident wavelength is varied, **Figure 6.8** plots the curve of the ratio η versus wavelength. It can be seen that unidirectional SPPs excitation of more than 90% can be achieved over a broad spectrum from 460 nm to 530 nm. It should be noted that the proposed structure also works well for the spectrum range that is not shown in the figure, although the unidirectional SPPs excitation efficiency at other wavelengths may fall below 90 %.

Figure 6.8 Unidirectional SPPs excitation capability (in term of the ratio η) of the structure from 460 nm to 530 nm.

6.2.3.2 Variation in the incident angle

Simulations also show that variation in the incident angle has negligible effect on the functionality of the structure. Since the wave vectors used to control the SPPs

propagation direction are generated by the asymmetrically arranged MDM slot itself, which is an intrinsic property of the structure. Variation of incident angle does not have great effect on its field manipulation capability. As shown in **Figure 6.9**, the ratio η only changes slightly when the incident angle is varied from -80° to 80° .

Figure 6.9 Unidirectional SPPs excitation capability (measured in term of the ratio η) of the structure at different incidence angles. The incidence wavelength is fixed at $\lambda=515$ nm.

6.2.3.3 Variation in the geometric parameters

Simulations also reveal that a small variation in geometry (such as width and length) of the structure has little effect on its functionality. Theoretically, variation in the geometry of the structure will affect the transverse wave vectors of the scattered waves transmitted through the slot. However, from the simulation results, it seems that a small variation in geometry only modifies the transverse wave vectors transmitted through the slot slightly. The effect of the slot width on the performance of the proposed structure is investigated first. In the simulations, the slot width is varied from 50 nm to 80 nm. The filling ratio of the dielectric is maintained as 50% (e.g., the width of the dielectric inclusion is 25 nm for an overall slot width of 50 nm) in all the simulations. As shown in **Figure 6.10 (a)**, the performance of the structure does not vary much when the slot width is increased from 50 nm to 90 nm. Next, the effect of

the filling ratio of the dielectric in the slot on the performance of the structure is evaluated. As shown in **Figure 6.10 (b)**, the width of the dielectric is varied from 15 nm to 35 nm for a 50 nm slot. Although there are some variations in the ratio η , the unidirectional SPPs excitation capability achieved is over 80%.

Figure 6.10 Effect of the geometry of the slot on the unidirectional SPPs excitation capability (measured in term of the ratio η) of the structure with the incident wavelength fixed at $\lambda=515$ nm. (a) The width of the slot width is varied from 50 nm to 80 nm. (b) For a 50 nm slot, the width of the dielectric is changed from 15 nm to 35 nm.

Based on the above simulations, it can be seen that the proposed structure for unidirectional SPPs excitation can perform consistently under various conditions such as variation in incident wavelength, incident angle and geometric parameters.

6.2.4 Beam enhancement by multiple slots

The proposed structure only relies on the geometric and material to realize unidirectional SPPs excitation. It is possible to enhance the strength of the excited SPPs beams simply by employing multiple slots. **Figure 6.11 (a)** illustrates the layout of the unidirectional SPPs generator consists of three slots. The width of each slot and the inter-distance between the adjacent slots are 50 nm and 170 nm, respectively. **Figure 6.11 (b)** shows the energy distribution of the unidirectional SPPs generator at

$\lambda=515$ nm. In the figure, the SPPs intensity at the output surface of the unidirectional SPPs generators with one slot and three slots are plotted. It can be seen that, the SPPs intensity at the positive x -axis can be enhanced when multiple slot are used.

Figure 6.11 Enhancement of SPPs beam intensity by using multiple partially filled MDM slots. (a) Energy distribution at the output surface of the SPPs generator with three slots. (b) Comparison of the SPPs beam intensity at the output of the SPPs generators with one slot and three slots.

In summary, a new scheme for unidirectional launching of SPPs is proposed and demonstrated. The proposed SPPs generator can be well scaled into nanometer regime, work over a wide spectrum and at nearly arbitrary incidence angle, and can be fabricated with a high level of tolerance to geometric defects. Multiple slots can be combined together to enhance the unidirectional launching of SPPs.

6.3 Application of the unidirectional SPPs generator for imaging

6.3.1 Planar magnifying device with sub-wavelength resolution

In this section, a planar magnifying lens is proposed. Such lens consists of two symmetrically arranged unidirectional SPPs generators and a multilayered MD structures. It provides one-dimensional resolution in the direction perpendicular to the slot. From the theoretical analysis and numerical simulations in the previous section, it can be seen that the unidirectional SPPs generator is capable of coupling with wave component with high wave vector components. Thus it can be used as a scanning probe to detect the near-field information of an object. Due to its unidirectional SPPs generation capability, the collected near-field information can be projected into only one direction. Thus, if two closely-spaced unidirectional SPPs generators are used as the scanning probes, it is possible to project the collected information from each of them into opposite directions. By combining the two unidirectional SPPs generators with a multilayered MD structure with hyperbolic dispersion relation, it is possible to magnify the near-field information by the two unidirectional SPPs generators. Thus, such structure can mimic the function of a magnifying lens. In the following section, the planar magnifying lens will be investigated.

6.3.1.1 Structure and mechanism

Figure 6.12 shows the schematic of the planar magnifying lens with labeled materials and dimensions. It consists of a multilayered silver-alumina (Ag-Al₂O₃) structure covered by a Cr layer with two partially filled slots. The thicknesses of individual Ag and Al₂O₃ layers are 20 nm and 40 nm, respectively. The total thickness of the multilayered Ag-Al₂O₃ structure is 440 nm. Based on the functionality of each component, the planar magnifying lens can be divided into two blocks. The first block

(Block 1 in **Figure 6.12**) is the two symmetrically arranged unidirectional SPPs generators which are used as probes to collect the near-field information. The near-field information collected from object A and object B can be converted into SPPs beams propagating along the negative and positive x -axis, respectively. The second block (Block 2 in **Figure 6.12**) is the multilayered Ag-Al₂O₃ structure which is used to split the two SPPs beams with an angle θ according to its hyperbolic dispersion relation. At the output of the multilayered Ag-Al₂O₃ structure, the separation of the two images (A' and B') can be easily magnified above the diffraction-limit. Thus it is possible to integrate the proposed planar magnifying device with conventional optical systems.

Figure 6.12 Structure and mechanism of the planar magnifying lens. A' and B' are the images of the two objects "A" and "B". θ is the beam splitting angle which is determined by the multilayered Ag-Al₂O₃ structure.

In order to make the planar magnifying device working properly, two requirements should be met. Firstly, the unidirectional SPPs generators should be capable of converting most of the near-field information from the object into only one SPPs beam. This requirement should be easily met since the unidirectional SPPs generator has a very high efficiency. Secondly, the multilayered Ag-Al₂O₃ structure should also provide enough magnification of the two beams at the output surface. This requirement can be achieved by engineering the dispersion relation of the multilayered

Ag-Al₂O₃ structure through various methods, such as varying the frequency, changing the thickness of the Ag or Al₂O₃ layers and increasing the total thickness of the structure. The magnification of the planar magnifying lens is primarily determined by the multilayered Ag-Al₂O₃ structure. The hyperbolic dispersion relation of the multilayered Ag-Al₂O₃ structure provides the key to the preferred propagation direction of the beams. The beam splitting angle is bounded by the half-angle between the asymptotes of the hyperbola [20], which can be estimated by

$$\theta = \tan^{-1} \left(\sqrt{\frac{\varepsilon_y}{\varepsilon_x}} \right) \quad (6.6)$$

where ε_x and ε_y are the effective permittivity along transverse and normal direction, respectively. Based on the EMT, they are related to the permittivities of the Ag and Al₂O₃ by the following equations

$$\varepsilon_x = p\varepsilon_{Ag} + (1-p)\varepsilon_{Al_2O_3} \quad (6.7)$$

$$\varepsilon_y = \frac{\varepsilon_{Ag}\varepsilon_{Al_2O_3}}{p\varepsilon_{Al_2O_3} + (1-p)\varepsilon_{Ag}} \quad (6.8)$$

6.3.1.2 Numerical simulations

The planar magnifying lens is numerically simulated by COMSOL. In the simulations, the two symmetrically arranged unidirectional SPPs generators are separated with a center-to-center distance of 45 nm. The slot width is 50 nm and the filling ratio of Si₃N₄ is 50%. The permittivity of Ag is extracted from reference [120], while the permittivity of the Al₂O₃ and Si₃N₄ are taken as 3.15 and 4, respectively. **Figure 6.13 (a)** shows the energy flow distribution of the planar magnifying lens when two 45 nm-spaced point sources ($\lambda=533$ nm) located at the plane 10 nm away from the Cr layer are being imaged. It clearly shows that the beam originating from the point

source "A" and "B" split in the negative and positive x -axis direction, respectively. And the two 45 nm-spaced point sources are effectively magnified to a much larger separation at the output surface. To qualitatively evaluate the magnification ratio, the beam intensity at the output surface is plotted in **Figure 6.13 (b)**. As shown in the figure, the two 45 nm spaced objects are magnified to 1590 nm at the output surface, indicating that a magnification ratio of 35 times can be achieved with the structure.

Figure 6.13 Image of two 45 nm-spaced point sources ($\lambda=533$ nm) by the planar magnifying lens. (a) Energy flow distribution inside the planar magnifying lens. The blue solid line represents the input surface located at the plane 10 nm from the Cr surface. The red dashed line represents the output surface. (b) Beam intensity measured at the input surface (blue solid line) and output surface (red dotted line).

Next, the magnification ratio of the planar magnifying lens is numerically evaluated and compared with the theoretical calculations. The magnification ratio can be approximated by calculating the half-angle between the asymptotes of the hyperbola of the dispersion relation of the multilayered Ag- Al_2O_3 structure. At 533 nm,

the permittivity of Ag and Al_2O_3 are $-10.19+0.83i$ and 3.15, respectively. The half-angle θ calculated by equation 5.5 is 64° , which is close to the 58° beam splitting angle estimated from the simulation results. Note that the beam splitting angle is determined by the intrinsic properties of the multilayered Ag- Al_2O_3 structure, and the variation of the local fields inside the slot will not alter the beam splitting angle. Thus, there will be no compatibility issue for integrating the multilayered Ag- Al_2O_3 structure with the unidirectional SPPs generators. This was verified by numerical simulations. **Figure 6.14** shows the energy distribution in the multilayered Ag- Al_2O_3 structure covered by a Cr layer with a 50 nm wide slot. It can be seen that the beam splitting angle of the simulated structure is exactly the same as that of the planar magnifying lens.

Figure 6.14 Beam splitting in the multilayered Ag- Al_2O_3 structure covered by a Cr layer on which a 50 nm wide slot is opened. The wavelength of the point source is 533 nm.

Based the performance of the unidirectional SPPs generator discussed in section 6.1, it is evident that the two beams measured at the output surface are indeed from their respective sources. To verify the results, the point source "A" is disabled while the other parameters are maintained the same as in previous simulations. As shown in **Figure 6.15 (a)**, only one beam exists in the multilayered structure when the point source "A" is disabled. **Figure 6.15 (b)** shows the beam intensity measured at the output surface. As shown in the figure, the peak intensity at the output surface when two point sources are imaged is around 11. For the case when only one point source is imaged, the peak intensity is exactly the same (**Figure 6.13 (b)**). This means that the

two slots working independently to detect the near-field information of the objects, and there is basically no crosstalk between them. Thus the two beams measured at the output surface are indeed from their respective sources.

Figure 6.15 Imaging of one point source by the planar magnifying device. (a) Energy flow distribution inside the planar magnifying device. (b) Beam intensity measured at the output surface.

As the beam splitting angle is closely related to the hyperbolic dispersion relation of the multilayered Ag- Al_2O_3 structure, it is possible to tune the beam splitting angle by engineering the hyperbolic dispersion relation by adjusting the thickness of the Ag layer or varying the incident wavelength. Thus for a planar magnifying device with fixed geometry, its magnification ratio can be tuned simply by varying the incident wavelength. In addition, since the two unidirectional SPPs generators are the key components used to collect the near-field information of the two closely spaced objects, their unidirectional SPPs excitation efficiency should not be compromised when the incident wavelength is varied. In section 6.2.3.1, it is shown that the

unidirectional SPPs excitation efficiency will not be affected much when there is a red shift in the wavelength. Thus it is possible to further increase the magnification ratio by using a longer wavelength. As shown in **Figure 6.16**, a magnification ratio of 41 times can be achieved by the lens when the incident wavelength is 560 nm. The magnification can be further increased by using a thicker multilayered Al_2O_3 -Ag structure. As long as there is detectable light at the output, the magnification of the device is unlimited. Benefited from the efficient magnifying scheme, the images can be easily magnified above the diffraction-limit at the output surface of the lens.

Figure 6.16 Imaging of two 45 nm-spaced point sources ($\lambda=560$ nm) by the planar magnifying lens. (a) Energy flow distribution inside the planar magnifying device. (b) Beam intensity measured at the input surface (blue solid line) and output surface (red dotted line) and output surface (red dotted line).

Based on the above analysis, the proposed planar magnifying lens can distinguish two closely-spaced objects and magnify the imaging to a separation beyond the diffraction-limit. With the planar input surface and magnified image at the

output surface, sub-wavelength imaging of a broad luminescent object can be realized by scanning along the x direction over the object. For example, a scanning step length can be set to the summation of the widths of the two slits and the chromium between them. The information from the two output beams can be recorded by a CCD camera during scanning then be inputted to a computer for image reconstruction and processing. In order to obtain the two-dimensional super resolved image of the object, one needs to implement the same process and obtain the information in another direction.

6.3.2 Configuration of the lens for imaging of objects in micro channel

Instead of using the proposed planar magnifying lens as a scanning probe, it is more practical to combine it with a micro channel to image the object in a fluid environment for chemical/biomedical applications. As illustrated in **Figure 6.17**, the objects under the observation flow through the micro channel. The diffraction limited feature of the objects can be captured by the two unidirectional SPPs generators and magnified by the multilayered MD structure. If the magnification is high enough, it should be possible to attach a commercial available detector to the output surface of the lens and retrieve the images directly. It could be possibly fabricated as a lab-on-chip device for high performance imaging.

Figure 6.17 Configuration of the planar magnifying device imaging of objects in micro channel.

6.3.3 Limitations of the planar magnifying lens

The proposed planar magnifying lens provides an innovative way for sub-wavelength imaging with a magnification. It has a planar input and output surface, and the magnification ratio can be easily tuned by varying the frequency. However, there are several issues may limit the practical application of such lenses. The major limitation of the planar magnifying lens is that the demonstrated lens can only resolve two points, which limits the imaging areas of such lenses. Although more than two points can be imaged by proper design (e.g. using more scanning probes to detect more points), the imaging area of such lenses is still limited. In addition, the low transmission efficiency of the multilayered MD structures may also cause problems in real applications. The low transmission efficiency problem is a common problem of the MD structures, which can be solved by using low loss materials or gain materials to compensate the loss. The proposed planar magnifying lens can be used for a variety of applications including imaging, nanofabrication, optical communication and high sensitive sensing. Although the imaging area of the lens is limited, such kind of device has a high potential to visualize the objects in a micro channel, which can be configured as a lab-on-a-chip device for biomedical imaging.

6.4 Summary

In this chapter, a new scheme on unidirectional SPPs excitation is proposed and numerically investigated. The proposed scheme only relies on the geometric manipulation of the energy distribution inside a partially filled slot, and it shows many advantages over the previously proposed schemes such as compact device dimension (lateral width of 50 nm and beyond can be achieved), insensitive to the incident angle and broad working spectrum. Moreover, as the performance of the structure for unidirectional SPPs excitation does not change when its dimension is varied slightly, the device has a strong tolerance to fabrication defects. This makes the real implementation of the scheme possible.

In the second part of this chapter, a planar magnifying lens is proposed by combining the unidirectional SPPs generators with a multilayered MD structure. The proposed lens has a very effective magnification scheme and the separation of the images can be easily magnified above the diffraction-limit at the output surface of the lens. Such planar magnifying lenses has great potential for imaging of objects in a micro channel and can be configured as a lab-on-chip device for high performance imaging.

Chapter 7. Conclusions and future works

This chapter concludes the studies done in this PhD project and proposes the recommendations for future research. The outlook of the proposed structures for other applications is also discussed.

7.1 Conclusions

In conclusion, this project focused on the design and simulations of plasmonic metamaterials for sub-wavelength imaging. Four types of plasmonic metamaterial structures were investigated, namely the multilayered MD structures, the hyperlens, the dielectric nanorod chain array embedded in the metal, and the planar magnifying lens. Based on the understanding of these structures from fundamental physics, their applications for sub-wavelength imaging were proposed and demonstrated. The major conclusions of this thesis are:

1. The imaging performance of the multilayered MD structures are primarily related to the super-guiding and transmission properties. In order to obtain an optimized performance, both mechanisms should be accounted. The super-guiding can be achieved by creating a strong anisotropy while the transmittance of the multilayered MD structures depends on the material losses. The optimized super-guiding condition and high transmission condition cannot be satisfied simultaneously. The proposed FoM accounts both super-guiding and transmission and a well-balanced value can be figured out by the FoM. It is found that for multilayered MD structures made of silver and a dielectric with permittivity of 5, the highest FoM occurs at $\lambda=400$ nm, and the corresponding optimized filling ratio is 0.428. The FoM works for both planar MD

structures and hyperlenses, and it can be used as a rule for optimizing the imaging performance of the multilayered MD structures.

2. The transmission of hyperlens differs from that of the multilayered planar MD structures. The accessible range of the evanescent wave of the hyperlens depends on its inner radius and outer radius, and it is larger than that of the multilayered planar MD structures. As a result, the hyperlens has a higher resolving power. Numerical simulations showed that, under 400 nm illumination, a hyperlens with inner radius of 240 nm and outer radius of 540 nm can clearly resolve the two 80 nm spaced slits, while the multilayered planar MD structures cannot. For the hemispherical hyperlens, it can work with normal incident light with the electrical field in any polarization direction. A full image of an object can be obtained by taking the superposition of the images obtained under different polarization directions.

3. Both the metallic/dielectric nanorod chains support guided plasmon modes with confinement below the diffraction-limit. The metallic nanorod chain under longitudinal polarization and the dielectric nanorod chain under transverse polarization are typical right-handed transmission line configurations which support forward propagation modes with higher transmission. When the thickness of the metal spacer layers is kept small, it is possible to achieve a higher transmission by the dielectric nanorod chain than its complementary structure. The dielectric nanorod chain also exhibits a stronger light-matter interaction and better energy confinement.

4. It is possible to realize a pixel-to-pixel metamaterial lens using an array of dielectric nanorod chains embedded in the metal. Instead of using metal as the major transmission medium, the proposed metamaterial lens uses the lossless dielectric nanorods. The metamaterial lens constructed by dielectric nanorod chains embedded in the metal showed a higher resolution and much longer transmission than the metallic

nanorod structure. At 560 nm, a resolution of 50 nm was demonstrated by the dielectric nanorod chain lens.

5. Unidirectional excitation of SPPs can be achieved by a partially filled metallic slot. The proposed scheme only relies on the geometric manipulation of the energy distribution inside a partially filled slot, and it shows many advantages over the previously proposed schemes. These include compact device dimension (lateral width of 50 nm and beyond can be achieved), insensitive to the incident angle and broad working spectrum. Moreover, the performance of the structure for unidirectional SPPs excitation does not vary much with its dimension, which makes the real implementation of the scheme easier.

6. It is possible to realize a planar magnifying lens by combining the SPPs generators and multilayered MD structure together. The two unidirectional SPPs generators serve as the scanning probes while the multilayered MD structure provides magnification. At 533 nm, a resolution of 45 nm and a magnification ratio of 41 times were achieved. Such planar magnifying lenses have great potential of being configured as a lab-on-chip imaging devices.

7.2 Future works and outlook

7.2.1 Future works

Numerical simulations provide a convenient way for device design and optimization. The numerical results obtained in this work can be used as general guidelines for experimental demonstration of the proposed metamaterial structures. The future work of this research should focus on the experimental verification of the theory and simulation results, which are summarized as the following:

1. The multilayered MD structures including the hemispherical hyperlens will be fabricated and tested. For imaging purpose, the surface roughness and particle size of the fabricated metal/dielectric film play important roles in determining the performance of the device. We have set up a magnetron sputtering system in the early stage of this PhD work and optimized the deposition conditions of various materials including Ag, Au, Cr, SiO₂, Si₃N₄ and Al₂O₃. The next stage of this work will focus on the experimental demonstration of sub-wavelength imaging by the multilayered MD structures. The example of the structure is illustrated in **Figure 7.1**, in which a diffraction-limited grating is used as the object; the incident light is back-illuminated on the grating, and the image is collected at the output surface by a SNOM probe.

Figure 7.1 A multilayered MD structure for sub-wavelength imaging.

The possible fabrication processes and testing setup of the hemispherical hyperlens are illustrated in **Figure 7.2 (a)** and **Figure 7.2 (b)**, respectively. The fabrication processes can be divided into four steps. These include: 1) deposition of 300 nm thick Cr mask layer on quartz substrate, followed by focused ion beam (FIB) milling of small holes, 2) formation of the hemispherical shape by buffered oxide etch (BOE) 3) deposition of multilayered MD films by magnetron sputtering and 4) deposition of 50 nm thick Cr layer, followed by FIB milling to create diffraction

limited objects. As illustrated in **Figure 7.2 (b)**, the characterization of such structures can be performed on an inverted microscope with an oil immersion objective lens and polarized incident light. The image can be collected by a high sensitivity image sensor.

Figure 7.2 (a) Fabrication processes and (b) experimental setup of the hemispherical hyperlens.

2. The dielectric nanorod chains discussed in chapter 5 could be possibly realized with the assistance of current nanofabrication systems such as electron beam lithography (EBL) and FIB. **Figure 7.3 (a)** shows the proposed processes. A 100 nm thick Cr layer should be deposited on a quartz substrate, followed by a 200 nm thick Ag layer on the top. Then a chain of nanoholes penetrating the top Ag layer are milled by FIB and filled with SiO_2 . Next, a small nanohole penetrating both the Ag layer and Cr layer is created at the end the nanohole chain. In the fabrication processes, the most difficult part is the milling of closely spaced nanoholes with well-defined shape and dimension. We have successfully fabricated samples in larger dimension as shown in **Figure 7.3 (b)**. The following work will be focused on the optimization of the processes and reduction of the device dimension. To test the fabricated samples, a linearly polarized light can be back-illuminate from the quartz substrate. The small nanohole serves as a diffraction limited light source, and the light guided along the

dielectric nanorod chain can be collected by a SNOM probe. To investigate the imaging properties, multiple rows of the dielectric nanorod chains can be fabricated, and the image can be recovered by scanning over the sample by the SNOM.

Figure 7.3 (a) Fabrication processes and experimental setup of the dielectric nanorod chain embedded in Ag film. (b) Fabricated dielectric nanorod chain in larger dimensions.

7.2.1 Outlook

It should be noted that the manipulation of light beyond the diffraction-limit serves many more purposes than imaging alone. Although, in this thesis, the author focused on exploring the sub-wavelength imaging capabilities of the plasmonic metamaterials, a variety of scientific fields such as data storage, optical communication and nanolithography will benefit from the further increase of the optical confinement. In this section, as the ending of this thesis, the potential applications of the investigated plasmonic metamaterials in other fields are discussed briefly in the following paragraphs.

1. The multilayered MD structures discussed in Chapters 3 and 4 of this thesis represent strong anisotropic metamaterials. In addition to imaging, such metamaterials can be used for plasmonic lithography, waveguiding, directive wave collimators, and optical communication.

2. The metallic/dielectric nanorod chains discussed in Chapter 5 are metallic nanostructures characterized by strong light-matter interactions. Due to the excitation of LSPs, they are also possible for surface enhanced Raman spectroscopy (SERS), optical data storage, waveguiding and enhancing the light absorption efficiency of solar cells. The main advantage of the dielectric nanorod waveguide is that they can be fabricated on metal layers on which the optical signal and electrical signal can co-exist. Thus, such dielectric nanorod chains can be an ideal waveguide in hybrid optical-electrical circuits.

3. In addition to imaging, the unidirectional SPPs generator can be possibly used as a chemical/biomedical sensor. Due to the plasmonic nature of the unidirectional SPPs generator, it is very sensitive to the permittivity of the ambient medium. For the partially filled slot waveguide, the energy confinement ratio between the low-index region and high-index region is proportional to the square root of $\epsilon_{high}/\epsilon_{low}$, where ϵ_{high} and ϵ_{low} are the permittivity of the low-index and high-index materials, respectively. At the silver surface, the large field enhancement of the SPPs localized at the silver surface also makes it very sensitive to the change in the permittivity of the adjacent dielectric. The overall sensitivity of the structure is the combined effect of the two processes. Thus, it can be used as an extremely sensitive device for monitoring the permittivity of the ambient medium.

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Journal papers

1. **Dongdong Li**, Dao Hua Zhang, Changchun Yan, Yueke Wang, Tao Li, and Zhengji Xu, "Planar plasmonic metamaterial composites for deep-subwavelength imaging with magnification," in preparation.
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