ENGINEERING ELECTROMAGNETIC WAVE PROPERTIES
USING SUBWAVELENGTH ANTENNAS STRUCTURES

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By
Shiyi Wang

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ABSTRACT

ENGINEERING ELECTROMAGNETIC WAVE PROPERTIES USING SUBWAVELENGTH ANTENNAS STRUCTURES

Name: Wang, Shiyi
University of Dayton

Advisor: Dr. Qiwen Zhan

With extraordinary properties, generation of complex electromagnetic field based on novel subwavelength antennas structures has attracted great attentions in many areas of modern nano science and technology, such as compact RF sensors, micro-wave receivers and nano-antenna-based optical/IR devices.

This dissertation is mainly composed of two parts. For the first part, the idea of plasmonic localization in optical range is transferred and utilized for generating confined fields with high enhancement in RF range. A subwavelength modified bowtie antenna in RF range is designed for generating strong broadband field enhancement in its extended feed gap. The strongly enhanced RF field within the gap can be applied to directly modulate guided optical wave propagating in a waveguide, which enables to realize indirect RF signal sensing through photonic methods. Systematic exploration for modified bowtie antennas and its substrate effect has been given in this part.
In the second part, the RF antenna design idea is extended to infrared and optical range based on antenna scaling theory specific for this spectrum. Both transmission and reflection types of metasurface structures have been designed and proposed to obtain optical needle field with a flat-top longitudinal intensity of depth of focus $5\lambda$. With fine adjustment of different nano-antenna structures, both of the metasurfaces enable to generate complex vectorial field with spatial radial polarization, whose amplitude modulation range covers 0.07 to 1 with binary phase control. Then the scattered field can be tightly focused by a high numerical aperture (NA) lens in order to generate longitudinally polarized flat-top field along propagation direction. By exploring the subwavelength antennas’ mechanism and connections between different frequency regions, this dissertation is expected to provide general guidance for design and characterization of next-generation subwavelength antennas structures with extraordinary electromagnetic wave properties.
Dedicated to my parents and my girlfriend Yijia
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<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical aperture</td>
</tr>
<tr>
<td>SLM</td>
<td>Spatial light modulator</td>
</tr>
<tr>
<td>PEC</td>
<td>Perfect electric conductor</td>
</tr>
<tr>
<td>NSOM</td>
<td>Near-field scanning optical microscope</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>FIB</td>
<td>Focus ion beam</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-couple device</td>
</tr>
<tr>
<td>MIM</td>
<td>Metal-Insulator-Metal</td>
</tr>
<tr>
<td>HWP</td>
<td>Half wave plate</td>
</tr>
<tr>
<td>QWP</td>
<td>Quarter wave plate</td>
</tr>
<tr>
<td>RP</td>
<td>Radial polarizer</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra high frequency</td>
</tr>
<tr>
<td>OBJ</td>
<td>Objective lens</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>EMW</td>
<td>Electromagnetic wave</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
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<tr>
<td>FP</td>
<td>Fabry Perot</td>
</tr>
<tr>
<td>EO</td>
<td>Electro optics</td>
</tr>
<tr>
<td>PCW</td>
<td>Photonic crystal waveguide</td>
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<tr>
<td>CW</td>
<td>Continuous wave</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder interferometer</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon on insulator</td>
</tr>
<tr>
<td>FE</td>
<td>Field enhancement</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>MMW</td>
<td>Millimeter wave</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal–oxide–semiconductor</td>
</tr>
<tr>
<td>DOF</td>
<td>Depth of focus</td>
</tr>
<tr>
<td>AF</td>
<td>Array factor</td>
</tr>
<tr>
<td>ONF</td>
<td>Optical needle field</td>
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CHAPTER 1
INTRODUCTION

Antennas are devices that convert freely propagating radiation into localized energy and vice versa. In general cases of radio frequency range (RF), it usually works as a transmitter or receiver, which enables to radiate the localized energy from the current as free electromagnetic waves, or intercept some of the electromagnetic waves to produce a terminal voltage respectively [1]. It has already been well developed in tremendous applications, such as radio broadcasting, radar, communications, cell phones and etc. On the other hand, optical antennas have shown the promising properties of controlling and manipulating optical radiations based on its flexibility and nano-scaled dimensions. As counterparts of traditional antennas, they provide novel approaches for realizing polarization manipulation [2, 3], chemical sensing [4], photodetection [5], electrical and magnetic field enhancement [6, 7], and spectroscopy [8].

For traditional microwave antennas, the functional resonance dimensions generally abide by the well-known half-wavelength principle, which is easily accessible to fabrication availability with relatively low manufacture requirements. While due to the challenging nano size of optical antenna devices, their development has been restricted by the technical difficulty for rather a long time.
As novel nano-technologies begin to offer dependable practice support, optical antennas are produced with the accuracy as low as several nanometers, resulting in a great amount of opportunities for nano-devices. Many prototype optical antennas, such as rod antennas [9], bowtie antennas [10], Yagi-Uda antennas [11, 12] and etc., have been derived from their analogues of microwave antennas by scaling down the dimensions to optical range. Not only do the new prototypes inherit their original properties, but some of them display extraordinary abilities, such like fluorescence detection by bowtie aperture antenna [4] and diabolo antennas for photothermal heat generation [13].

This dissertation is mainly composed of two parts. For the first part, the idea of plasmonic localization in optical range is transferred and utilized for generating confined fields with high enhancement in RF range. A subwavelength modified bowtie antenna in RF range is designed for generating strong broadband field enhancement in its extended feed gap. This modified bowtie antenna is comprised of a conventional bowtie antenna with capacitive extended bars attached to the apex points of the bowtie. The feed gap between the two capacitive bars is separated with a deep subwavelength width for the generation of enhanced local electrical field. Based on three dimensional finite element method model, the properties of this antenna design are explored systematically. Highly enhanced electrical field is created between the extended bar under radio frequency (RF) illumination. The strongly enhanced RF field within the gap can be applied to directly modulate guided optical wave propagating in a waveguide embedded in the substrate underneath the feed gap. This work will build up a bridge between devices in the RF and optical frequency regimes that may find many potential applications in RF photonic devices and systems.
In the second part, the RF antenna design idea is extended to infrared and optical range based on antenna scaling theory specific for visible and infrared wavelength. Firstly, a novel gold transmission type metasurface composed of carefully designed slot antennas is proposed for optical needle field generation. Particularly, each of the slot antennas behaves as a local linear polarizer, which can modify the amplitude and phase for the cross-polarized component of the scattered field. With appropriate excitation by normal incident light, this metasurface sample enables to form a scattered field with specific beam patterns and corresponding polarizations. Then the scattered field can be tightly focused by a high numerical aperture (NA) lens in order to obtain longitudinally polarized flat-top field along propagation direction. The so-called optical needle field is expected to be characterized with near-field scanning optical microscope (NSOM) setup. Fabrication of the metasurface structure is realized by using Focused Ion Beam (FIB), which is more suitable for the proposed design. Moreover, to simplify the setup of optical needle field generation system based on transmission type metasurface and increase its scattering efficiency, a reflection type metal-insulator-metal (MIM) metasurface composed of hybrid optical antennas is also proposed and proved numerically. Behaving as a reflection type segmented quarter-wave-plates (QWP), the MIM metasurface is designed to convert circularly polarized incidence into local linear polarization, and thus overall radial polarization with corresponding binary phases and desired normalized amplitude. Here periodic arrangements of double metallic nano-bars with perpendicular placement and single nano-bars respectively are applied for different modulation requirements while maintaining π/2 retardation. Meanwhile, a super-period of MIM nano-disks with different diameters configuration is used to deflect the undesired light for dark rings in the design, which leads the whole structure to be a hybrid
reflection metasurface structure. The proposed metasurface establishes a new class of compact optical components based on nano-scaled antennas, giving rise to compound functions for vectorial light generation.

In summary, this dissertation is proposed for engineering the novel light properties based on subwavelength antennas in optical, IR and RF ranges. By exploring the subwavelength antennas’ mechanism and connections between different frequency regions, a more advanced and universal theory is expected to be built up for antenna design and application. Although necessary modification for antenna theory is required for specific ranges, the fundamental orientation of antenna design is shared in all of the fields. With a generalized theory as guidance, more and more brilliant designs for practical applications will be proposed and illustrated with efforts. Thus the manipulation and utilization of novel properties for general electromagnetic fields can be realized with maximal flexibility.
CHAPTER 2
MODIFIED BOWTIE ANTENNA DESIGNED FOR STRONG BROADBAND FIELD ENHANCEMENT

2.1 Background of Bowtie Antenna

As one of the commonly applied structures, bowtie antenna has attracted significant attentions due to its simple design and stable broadband performance. Its applications range widely from UHF television receiver to nano-scaled optical antenna [4, 14, 15]. With infinite bow arm length, the bowtie antenna can be treated as an infinite antenna, whose characteristic parameter is mainly a function of flare angle and independent of frequency [16]. However, in practice, bowtie antenna actually has a resonant frequency with finite bandwidth, which is restricted by the finite length of each bow arm. This is because the bowtie antenna itself can be characterized as a $\lambda/2$ dipole antenna, whose resonant frequency mainly relies on the antenna dimension [16]. By scaling the antenna’s geometry, we can adjust its resonant frequency to achieve the design requirement, leading to flexible function over a wide range from visible light to microwave.
During recent years, researchers have explored various applications with bowtie structure, such as nano-sensing probe [4], nonlinear absorber [14], extreme-ultraviolet light generator [15] and quantum emitter [17]. In particular, planar metallic bowtie nano-antennas have shown broadband nano-scale light confinement and an enhancement factor of more than 1300 for the fluorescence of single molecules [18], which confirms the promising advantage of bowtie antenna for obtaining extremely high field enhancement within its feed gap.

By transferring the idea of plasmonic localization from optical frequency to radio frequency, high enhancement and confinement of electric field can be realized through bowtie antennas. With the two bowtie arms as receivers, a confined electric field with strong enhancement factor can be generated in the gap between them. In other words, the bowtie antenna can harvest incident electromagnetic wave and transform it into high power density field that is localized within the feed gap region, giving rise to many potential engineering possibilities. For example, it is feasible to obtain strongly enhanced electric field with RF bowtie antenna and utilize the locally enhanced RF field to directly manipulate light propagation in an optical waveguide embedded within the feed gap. Such a phenomenon may allow the detection of weak RF electric signals through optical means. In this part, we propose and systematically study the design of a modified RF bowtie antenna that is suitable for this application. In order to obtain strong field enhancement, related parameters for the antenna structure and the substrate that it sits on will be optimized.
2.2 Geometry and Simulation Method for Bowtie Antenna on lithium niobate substrate

The geometry of the proposed modified bowtie antenna device for strong field enhancement design is shown in Figure. 2-1 [19]. A planar gold bowtie structure is deposited on a lithium niobate substrate (LiNbO₃), whose refractive index can be controlled by the applied electric field intensity due to electro-optic effect, thus the modulation for optical waveguide embedded within it can be realized. With normal incident RF wave polarized along the Y-axis, a strongly enhanced uniform electric field is expected within the subwavelength feed gap region, whose dimension is as low as 1 µm. In order to obtain extended area with strong field enhancement, the corresponding apex of bowtie structure are attached with extended metallic bars, which can manage the resonance peak by shifting the total capacitance due to equivalent LC circuit principles. In this study, we fix the bowtie flare angle to be 60 degrees to reach the highest field enhancement. The thickness of the gold film is chosen to be 5 µm, which is far beyond the skin depth of gold at RF region.

A three-dimensional finite element method (FEM) model (COMSOL Multi-Physics) has been built and used for the electromagnetic field calculation. With appropriate optimization of the bowtie arm length, thickness of substrate and other related parameters, the resonance characteristics can be engineered to meet specific design requirements.
Figure 2-1 Geometry of the modified bowtie antenna on LiNbO$_3$ substrate. (a) Bowtie antenna under normal RF wave illumination with polarization oriented along bow arm axis (Y-direction). (b) Top view of bowtie antenna. (Bow arm length $l_1$; feed gap width $g$; capacitive extended bar length $l_2$, width $w$; bowtie thickness $t_1$; substrate thickness $t_2$; flare angle $\alpha$)
2.3 Modified Bowtie Antenna Based on LC Circuit Principle

Generally, the antenna system can be considered as a typical LC circuit, which is mainly composed of the inductive bowtie metallic arms and the capacitive bars filled with air, giving rise to the LC resonance determined by antenna geometry. For this work, we characterize this resonance effect by field enhancement ratio defined as \( r_{FE} = |E_{\text{obs}}/E_{\text{inc}}| \), where \( E_{\text{obs}} \) and \( E_{\text{inc}} \) are the electric field amplitudes at specific observation point and the incident plane respectively. First, we start with a free standing bowtie antenna with the bow arm length \( l = 170 \) µm and the feed gap width \( g = 1 \) µm without the metallic bars. Its peak frequency of \( r_{FE} \) extracted in the center of feed gap region is around 460 GHz, which matches the theoretical estimation of half wavelength antenna. Then, by attaching the extended metallic bars to the apex points of each bow arm, it not only introduces a new degree of freedom for adjusting the resonance frequency but also provides an increased feed gap region length with an enhanced electrical field within. Increasing the overall capacitance of bowtie results in a red-shift of the resonance frequency \( f_0 \) in free space. For the 90 micron long and 10 micron wide extended bars used in this study, a new resonance frequency \( f_0 \) is found to be centered at 325GHz with a full-width-at-half-maximum (FWHM) bandwidth of 360 GHz.

In the next step, a LiNbO3 layer is added to support the bowtie antenna as the substrate. It is well known that the resonance performance greatly depends on the substrate properties. For the case where the substrate fills the entire half-space underneath the antenna, the antenna can be regarded as immersed in an environment with effective permittivity \( \varepsilon_{\text{eff}} \)\(^{[20]} \), leading to a new resonance frequency \( f_R \) expressed as:
\[ f_R = f_0 \sqrt{\frac{1}{\varepsilon_{\text{eff}}}} = f_0 \sqrt{\frac{\varepsilon_{\text{sub}} + 1}{2}}, \] (2-1)

where \( \varepsilon_{\text{sub}} \) is the dielectric constant of LiNbO\(_3\) substrate, which is set as \( \varepsilon_{\text{sub}} = 29 - i0.06 \) at the RF range. A bowtie antenna on a substrate with finite thickness is expected to have a resonance frequency between \( f_0 \) and \( f_R \), which can be adjusted through controlling the substrate thickness.

Using the approach described above, a design of central frequency 100 GHz is realized through choosing the LiNbO\(_3\) substrate thickness \( t_2 = 220 \mu m \) (shown in Figure. 2-2(a)). A field enhancement spectrum is obtained from the numerical model with a maximum field enhancement as high as 214 extracted at the feed gap center, and the FWHM bandwidth in this case reaches about 40 GHz. Further investigation shows that the electric power is mainly confined in the feed gap region, which is a typical dipole antenna performance [21]. Besides, as we can see from the inset of Figure. 2-2(a), capacitor-like performance is observed between the metallic bars with electric field lines diverging from one bar and concentrating at the other as driven by the Y-polarized incident. At the same time, to satisfy charge conservation for each of the bow arms, charges with opposite signs turn out and get localized at the edges of bowtie bottom, generating an overall dipole distribution. In order to better visualize the field distribution, the color scale of Figure. 2-2(a) inset has been saturated, while the electric field within the feed gap still dominates with most of energy being confined in that region. Hence, the resonance can be manipulated by adjusting the total capacitance through metallic bars and the inductance through bow arms.
The electric field distribution within the feed gap along the Z-axis is shown in Figure 2-2(b). From the side view of bowtie, each of the sidewalls that encloses the feed gap behaves like planar plates of a capacitor, resulting in a uniformly distributed electric field within the gap. Considering of fabrication feasibility, we keep the feed gap width to be 1 µm. Further shrinking of this dimension leads to even higher field enhancement, but the
fabrication will be challenging. When approaching to the edge of bowtie feed gap, the field enhancement tends to decrease. The field enhancement decays exponentially away from gap into the substrate. Based on this design, an enhanced electric field near the feed gap is created right below the interface, which is where the optical waveguide should be embedded.

2.4 Substrate effect on field enhancement due to Fano Resonance

As mentioned before, without the LiNbO$_3$ substrate, the free standing modified bowtie antenna gives a resonance peak response at 325 GHz with an FWHM of about 360 GHz according to three-dimensional numerical modeling, while in the case with a 220-µm LiNbO$_3$ substrate, the resonant peak shifts to 100 GHz with a bandwidth of 40 GHz. Apparently, the introduction of substrate causes a red-shift by more than 200 GHz and a reduced bandwidth. Further exploration for modified bowtie model leads to the discovery of a Fano resonance induced by substrate [22, 23]. Fano resonance was initially introduced in quantum mechanical research about the autoionizing states of atoms [24, 25]. It exhibits a distinctly asymmetric shape due to the destructive interference between a narrow discrete resonance and a broad spectral line [26], giving rise to an asymmetric dip for resonance lineshape.

In general, Fano resonance can be realized by breaking the symmetry of the structure, which introduces high dielectric material as the substrate into the system. Under the contrast of dielectric environment, different resonance modes are excited, and the effective coupling between them forms the typical Fano asymmetric lineshape. In our case, Fabry-Perot effect behaves like the resonance with narrower bandwidth, since its coupling with
the incident RF field is less efficient than the bowtie dipole mode. As displayed in Figure. 2-3, its peak position is mainly driven by substrate properties. By increasing the substrate thickness, a red-shift of resonance frequency based on transmission spectrum is obtained, which follows formula [27]:

\[ \text{Trans}
\]
where \( f_{FP} \) stands for Fabry-Perot resonance frequency, and \( c_0 \) is the light speed in vacuum. Figure 2-3(b) confirms this relation by showing a perfect match between simulation and theory.

In the case when \( t_2 \) is 220 \( \mu m \), the substrate itself performs a Fabry-Perot resonance at 126GHz with an FWHM of 30GHz as shown in Figure 2-3(a) (plotted in orange dash-dot line). Compared with the FP effect, the bandwidth of bowtie dipole mode in Figure 2-2(a) tends to be broader. Due to the interaction between the FP resonance and the bowtie dipole resonance, the typical asymmetric dip caused by Fano resonance is obtained as shown in Figure 2-4. For a free standing bowtie antenna, there is only a single field enhancement peak with dipole mode distribution due to absence of FP effect interaction. As the FP peak

\[
f_{FP} = \frac{c_0}{2t_2 \sqrt{\varepsilon_{sub}}}, \tag{2-2}
\]
gets closer to the estimated $f_R$ (about 84 GHz) given by equation (2-1), it begins to play a role by changing the overall lineshape with an asymmetric dip. For the models with LiNbO$_3$ substrate, the dip locates near the maximum of field enhancement curve as a result of destructive interference. As the substrate increases from 200 µm to 240 µm, the position of asymmetric dip shifts to the lower frequency side because of the red-shift of FP resonance. At the same time, FP mode benefits the field enhancement by providing effective coupling through substrate as its peak approaches to the bowtie dipole resonance, resulting in an obvious increase for the field enhancement. Since the bandwidths of these two resonances have limited contrast with each other, the destructive interference between them may not be as strong as the one resulted from continuum state and discrete state in the ideal case [26]. Hence, the asymmetric dip seems to be not as pronounced, especially for the 240 µm thick substrate case. Nevertheless, it can be concluded that the high refractive index substrate introduces a non-uniform dielectric environment, which gives rise to the FP resonance and provides a fine adjustment for the desired resonance peak strength and location through a Fano-like interaction. The field enhancement can be further optimized through fine tune this Fano resonance between the dipole resonance of the bowtie antenna and the FP resonance arising from the substrate.

To understand the mechanism of Fano resonance in our case, the absorption curve of the model with 220 µm thickness is given as shown in Figure 2-5(a). From the quantum view, the absorption lineshape due to Fano resonance can be basically characterized by its absorption cross-section $\sigma_{abs}$ at photon energy $E$ as shown in formula (3) [28],
\[ \sigma_{\text{abs}} \propto \frac{(\epsilon + q)^2}{\epsilon^2 + 1}, \quad \epsilon = \frac{E - E_0}{\hbar \Gamma / 2} \]  

(2-3)

where \( \epsilon \) stands for the reduced energy determined by resonance energy \( E_0 (E_0 = \hbar \omega_0) \) and resonance width \( \Gamma \); \( q \) denotes the asymmetry factor, which depends on the phase difference \( \phi \) between the two resonances at time domain. As the phase \( \phi \) shifts, the overall lineshape

**Figure 2-5** (a) Absorption and transmission as a function of frequency \( (z = 220 \, \mu m) \); electrical field arrow plots for different modes (b)105GHz (c)110GHz (d)125GHz
will change from symmetric Lorentzian line shapes to Fano line shapes with different degree of asymmetry, which can be observed clearly when we manage the FP effect through substrate manipulation.

To further investigate its physics, a mode analysis is explored as plotted in the electrical field arrow picture of Figure 2-5(b) 2-5(c) 2-5(d). The bow-tie antenna shows a dipole bright mode distribution around 105GHz, which means the incident RF wave couples directly to the antenna due to its maximum dipole momentum [29]. Meanwhile, the field enhancement at feed-gap center is also very high according to Figure 2-2(a), since most of the coupled wave energy is designed to be concentrated within the region confined by capacitive metallic bars. On the other hand, as the frequency goes as high as 125GHz, the charges with opposite sign tend to come out and get localized at the bow-tie waist, generating the so-called quadruple mode as shown in Figure 2-5(d) [21]. This mode is also defined as dark mode, which means it cannot be excited directly from incident wave, but through symmetry breaking induced by high dielectric substrate. This is because the coupling between incident wave and antenna structure is limited due to its low total dipole moment, resulting in lower field enhancement as well. At 110 GHz, point c in Figure 2-5(a) represents a transitional state between the dipole mode and the quadruple mode, where bright dipolar mode starts to change into quadruple mode as shown in Figure 2-5(c). The destructive interference between the two modes causes local minimum at the absorption curve, leading to an asymmetric dip for the lineshape.
2.5 Application: Integrated Photonic Electromagnetic Field Sensor Based on Broadband Bowtie Antenna Coupled Silicon Organic Hybrid Modulator

2.5.1 Introduction

From our initial design, an integrated photonic electromagnetic field sensor based on broadband bowtie antenna coupled silicon organic hybrid modulator working at central frequency 10GHz has already been experimentally realized [30]. As shown in Figure 2-6, a modified bowtie antenna harvests incident electromagnetic waves, transforms it into high power density electric field within the feed gap, and directly interacts with the optical waves propagating along the EO polymer refilled slot photonic crystal waveguide (PCW) embedded within the feed gap. The refractive index of the EO polymer can be controlled by the applied resonant electric field due to EO effect. The defect mode frequency of the slot PCW is very sensitive to refractive index change of EO polymer; therefore, the spectrum position of the transmission edge can be shifted by electric field. This effect is used to electro-optically modulate the phase of a continuous wave (CW) laser input tuned closely to the transmission edge of the defect mode. This phase modulation is then converted to intensity modulation, by using an external arm to form a MZI structure. Finally, by measuring the modulated optical intensity at the output end, the weak electromagnetic field from free space can be detected through optical means.

The key parts of our photonic electromagnetic field sensor consisting of an EO polymer refilled silicon slot PCW phase modulator coupled with a gold bowtie-shaped antenna are shown schematically in Figures. 2-6 (a)-(e). An EO polymer, SEO125 from Soluxra, LLC, with a large $r_{33}$, low optical loss, and good temporal stability, is used to refill the silicon slot PCW. This EO polymer refilled silicon slot PCW with a slot width ($S_w$) of 320 nm is
band-engineered to achieve low-dispersion slowlight propagation over a broad wavelength range of 8 nm [31], as well as high optical mode confinement inside the EO polymer refilled slot. The slow-light enhanced effective in-device $r_{33}$ of this SOH modulator can be over 1000 pm/V [31], which is beneficial for high-sensitivity sensing. The slot PCW is

![Figure 2-6](image)

**Figure 2-6** (a) A schematic view of the key part of the electromagnetic field sensor consisting of an EO polymer refilled silicon slot PCW phase modulator and a bowtie antenna. An external arm combined with this phase modulator forms an MZI structure, converting phase modulation to intensity modulation. (b) SWG coupler. (c) Strip-to-slot mode converter. (d) Magnified image of slot PCW. (e) Tilted view showing the cross section of the antenna-coupled slot PCW, with dimension parameters and two levels of n-type silicon doping concentrations. Note: the EO polymer layer covered on top of the device is not shown in (b)–(e) for better visualization.
embedded in the feed gap of the bowtie antenna, and the silicon layer is selectively implanted with different ion concentrations for high frequency operation [32]. The bowtie antenna is used as a receiving antenna, driving electrodes, and poling electrodes. Here the bowtie antenna with capacitive extension bars has a simple design, and a broadband characteristic. With the two bowtie arms as receivers, a confined resonant electric field with strong enhancement factor can be generated in the gap between them [19].

2.5.2 Practical design and simulation results

After cautious consideration of the computation results and fabrication capability, we set the arm length to be 3mm for bowtie antenna with the SOI substrate as described before (SiO₂ 3 μm / Si 700 μm). The narrow feed gap width between the two capacitive bars is 8.4 μm, for the generation of highly enhanced local electric field under RF illumination. This gold antenna is designed with bow arms on silicon dioxide to avoid the impact of conductive silicon region. In the actual device fabricated on an SOI substrate, the top silicon region everywhere apart from the PCW region is entirely etched away, letting the buried oxide layer be directly underneath the bow arms to fit this design. The silicon handle underneath the buried oxide layer is taken into account in the simulation. As discussed before, with the feed gap width and capacitive bars fixed, the resonant frequency of a bowtie antenna is mainly determined by the length of each bow arm and the flare angle (L and α in Figure. 2-7(a)). This bowtie antenna structure together with the effective-medium approximated silicon RF dielectric constant and conductivity values is used for COMSOL Multiphysics simulation.
With bow arm length $L = 3$ mm and flare angle $\alpha = 60^\circ$, the bowtie antenna is optimized with a central resonant frequency at around 10 GHz, and a uniform electric field enhancement over the entire feed gap is created. Figure 2-7(c) shows the top view of the local resonant electric field amplitude inside the antenna feed gap at 10 GHz. The electric field is mainly confined in the feed gap region, which is similar to the performance of a typical dipole antenna as expected. Additionally, as explained above, the electric field is actually concentrated inside the slot of the silicon PCW, and this increases the FE even further. Figure 2-7(d) shows the FE spectrum from simulations, indicating that the electric

Figure 2-7(a) Schematic top view of the designed bowtie antenna. Arm length, $L = 3$ mm, and flare angle, $\alpha = 60^\circ$. (b) Magnified image of the feed gap region in (a). (c) Top view of electric field enhancement distribution inside the feed gap of the antenna. The electric field enhancement distribution is shown inside the EO polymer refilled slot at $y = 0.125 \mu m$, where $y = 0$ corresponds to the horizontal interface between the silicon layer and the buried oxide layer. (d) Variation of the field enhancement factor inside the slot versus incident RF frequency.
field radiation compressed inside the slot of the silicon PCW is enhanced by a maximum factor of $\sim 10,000$ at 10 GHz, with a 1-dB RF bandwidth over 9 GHz. This strongly enhanced RF field directly modulates the optical wave propagating along the EO polymer refilled doped silicon slot PCW which is embedded inside the feed gap. No extra connection lines between the antenna and EO modulator and no external electrical power supply are required. Furthermore, similar to a typical dipole antenna, the bowtie antenna has spatially wide angular beam width in its radiation pattern, which enables our sensor to detect electromagnetic fields from a large range of incident angles.

The fabrication work has been done by Chen’s group from the University of Texas at Austin [30]. To manufacture the proposed device, electron-beam lithography and reactive ion etching (RIE) are used for silicon slot PCW. The bowtie antenna structure is fabricated by electron-beam evaporation and photolithography. SEM images of the fabricated device are shown in Figure. 2-8.
Figure 2-8 (a) SEM image of the fabricated device. (b) Magnified SEM image of the yellow rectangular region in (a) shows the slot PCW region and bowtie antenna overlay. (c) SEM image of the new type mode converter for efficient coupling between strip waveguide to large-slot (320nm) PCW waveguide. (d) SEM image of cross section of the EO polymer refilled silicon slot PCW. PCs: photonic crystals. (e) Magnified SEM image of the dashed square area in (c).
2.5.3 Characterization

In order to demonstrate the broadband characteristics of the bowtie antenna in our fabricated device, a network analyzer (HP 8510C) is used to measure the $S_{11}$ parameter (reflection signal) of the bowtie antenna. A signal-ground microprobe (Cascade Microtech ACP40GS500) is used to couple RF power from the network analyzer into the bowtie antenna, and the $S_{11}$ parameter over a broad frequency range of 4-16GHz is recorded. The experiments are taken at the University of Texas at Austin by Chen’s group. Assuming negligible loss, the $S_{21}$ data can be inferred from the $S_{11}$ measurements, as shown in Figure 2-9, from which a broadband response can be clearly seen. The maximum response occurs

![Figure 2-9 Measured $S_{21}$ parameter of the broadband bowtie antenna. The inset shows a top-view microscope image of the fabricated device](image)

24
at 10GHz, which agrees well with the simulated maximum field enhancement at 10GHz in Figure. 2-7(d).

2.6 Application: Silica/Electro-optic Polymer Optical Modulator for MMW Receiving

As shown in Figure. 2-10, a silica/EO polymer phase modulator with an embedded bowtie antenna is proposed for MMW (millimeter-wave) receiving [33]. The device is fabricated on silica for low RF reflection and high sensitivity. The fabrication and experiment work is done by Peyghambarian’s group at the University of Arizona. The bowtie antenna design simulations showed extremely broadband response and correlates well with measured data. This is the first MMW modulator receiver to incorporate EO polymer as the active material. The device is compact, pigtailed with SMF-28 fiber for ease of integration, and requires only straightforward fabrication techniques for both the waveguide and the electrodes.

![Figure 2-10](image)

**Figure 2-10** (a) Bowtie antenna design with dimensions. A top view of the field enhancement distribution near the gap region at the EO polymer/silica substrate interface ($z = 0$) is shown in the inset. (b) Pigtailed antenna with UHNA1-SM28 transition fiber.
Again, we used COMSOL Multiphysics to study the RF response of the bowtie antenna integrated with the EO polymer waveguide. The cross section of the gap region of the bowtie antenna with an EO polymer groove waveguide integrated underneath is shown in Figure 2-11(a). An RF plane wave polarized in the y-direction illuminates the structure at normal incidence from the sol-gel side, which can modulate the refractive index of EO polymer through Pockels effect and thus the phase of optical propagating wave in the vicinity of groove region. The field enhancement (FE) factor is defined as the resonant electric field marked by the red dot in Figure 2-11 (a) divided by the incident field. Figure 2-11 (b) shows the FE factor measured at the center of the groove waveguide (red dot shown in Figure 2-11 (a)) versus the RF

Figure 2-11 (a) Schematic of the cross section of the gap region of the bowtie antenna with an EO polymer waveguide underneath used in the COMSOL model. (b) Field enhancement factor monitored at the center of the EO polymer waveguide (red dot shown in (a)) versus the input RF frequency showing an extremely broadband response with peak at 5 GHz. (c) Electrical field pattern at 5 GHz shows a dipolar type of resonance. A top view of the field enhancement distribution near the gap region at the EO polymer/silica substrate interface (z=0) is shown in the inset. (d) Field enhancement profiles at 5 GHz and 10 GHz across different layers at the center of the device (white dashed line shown in (a)).
frequency. This simulation results show that the compressed RF radiation is enhanced by a factor of 450 at 5 GHz and by a factor of 300 at 10 GHz inside the EO polymer waveguide. An RF 3dB-bandwidth of approximately 12 GHz is also observed. It should be noted that the FE factor would be much higher (>1000) at regions close to the corners of electrodes. However, the overlap between the enhanced RF field and the optical mode will mainly occur in the center region of the gap. Consequently, we choose the FE factor in the center of the EO polymer waveguide to characterize the device performance. The electric field pattern at 5 GHz across the entire bowtie antenna is illustrated in Figure. 2-11 (c). A dipolar type resonance can be clearly identified. The FE distribution within the antenna gap region at z=0 plane is also shown in the inset, demonstrating a fairly uniform FE distribution for the area where most of the overlapping with the optical mode will occur. Figure 2-11 (d) shows the FE factor profiles for both 5 GHz and 10 GHz across the device in the vertical direction (along the white dashed line shown in Figure. 2-11 (a)). It can be seen that the FE factor is the highest in the plane of the bowtie antenna electrodes and decreases away from it. Thus it would be beneficial if the optical mode profile is designed to be closer to the EO polymer/sol-gel interface. This device presents itself as an initial benchmark for future EO polymer-based MMW receivers and displays potential for a wide range of MMW detection due to its intrinsically fast electronic response. Therefore, RF-photonics combined devices offer a viable platform that may find important applications as RF photonic links, electromagnetic field measurement, phased array radar, and radio-over-fiber technology.

2.7 Systematic study for Bowtie Antenna on transparent glass and SOI substrate

In the last several sections, a modified bowtie antenna has been integrated with an electro-optic modulator in its feed gap to form a very sensitive electromagnetic wave sensor. For
the detection of electromagnetic waves, the interaction of the waves and the substrate materials needs to be considered, and a low-k dielectric substrate, such as a glass substrate, is desired to provide better microwave coupling [33]. In addition, some electromagnetic wave detectors previously demonstrated on silicon-on-insulator (SOI) substrates [30, 34] suffer from unwanted reflection and scattering from backside silicon handle [35], while, in comparison, a glass substrate can avoid this issue and improve the detection sensitivity. Therefore, a cost-effective transparent low-k glass substrate is explored in this part. Since the contrast of dielectric environment is limited in these cases, the Fano-resonance effect will be neglected. Here, a modified bowtie antenna on transparent glass substrate is computed, fabricated and characterized experimentally. The electromagnetic power that the bowtie antenna receives is measured by a microwave spectrum analyzer (HP 8560E) via a ground-signal (GS) microprobe (Cascade Microtech ACP40GS500).

In order to demonstrate the broadband characteristics of the fabricated bowtie antenna and to investigate the dependence of resonant frequency on the bowtie geometry, two groups of bowtie antennas without slot PCW are fabricated on glass substrates (Fisher Scientific 12-550C) through standard CMOS manufacturing process by Chen’s group. The first group of three bowtie antennas has a fixed arm length of 4.5mm, but flare angles of 30 degrees, 60 degrees and 90 degrees. The second group of five bowtie antennas is fabricated with a fixed flare angle of 60 degrees, but arm lengths varying from 3.5mm to 5.5mm in steps of 0.5mm that can cover a range targeted around an operating frequency of 10.5GHz. Their extension bars have a length of 300 μm, and the thickness of the gold film is chosen to be 5 μm, which is far beyond the skin depth of gold at the RF frequency of operation. Since
the capacitance effect of extended bars is quite limited due to its dimension comparing with the arm lengths, we will mainly focus on the influence of arm length and flare angle.

For the first group, we fix the arm length to be 4.5 $\mu$m, and then shift the flare angle $\alpha$. Here, the incident electric field is a normalized continuous plane wave linearly polarized along the antenna axis and impinges upon the antenna from the top. The vector network analyzer is used to measure the $S_{11}$ parameter (reflection signal) of these antennas over a broad frequency range of 1-20GHz via the GS microprobe. By assuming negligible loss,

![Figure 2-12](image)

**Figure 2-12** (a) Measured normalized transmission spectrum of bowtie antennas with different flare angles. (b) Correlation of measured resonant frequency with simulated resonant frequency at different flare angles. In (a) and (b), arm lengths are fixed at 4.5mm.
the normalized transmission signal can be inferred from the $S_{11}$ measurements, as shown in Figure 2-12 (a) and (b). The measured resonant frequency as a function of arm lengths is extracted from the figure, and then correlated with the simulated resonant frequency, as shown in Figure 2-12 (b). Apparently, there is dependence of resonance frequency on the flare angle, while keeping the arm length constant. Also, a broadband response can be clearly seen. Similarly, the measured resonant frequency as a function of flare angles is extracted from Figure 2-13 (a) and then correlated with simulated resonant frequency in Figure 2-13 (b). For longer bowtie arm or larger flare angle, the current flows through

![Figure 2-13](image)

*Figure 2-13* (a) Measured normalized transmission spectrum of bowtie antennas with different arm lengths. (b) Correlation of measured resonant frequency with simulated resonant frequency at different arm lengths. In (a) and (b), flare angles are fixed at 60 degrees
longer path to the gap, hence the effective antenna size is increased, leading to longer resonant RF wavelength, which corresponds to lower resonant frequency. The trend in measurement results agree with the simulations. It can be seen that there are still some deviations between the measured and simulated resonant frequencies. This could be due to several reasons, such as the difference of the dielectric constant of an actual glass substrate and that assumed in simulations, and slight variations of size and shape of fabricated bowtie antenna from idealized model due to fabrication error.

Next, to simulate the practical case for bowtie antennas integrated with an electro-optic modulator, we embed the slot PCW in the bowtie antenna at the feed gap region, whose width is adjusted to be 9.36 μm. Both the cases for SOI substrate (SiO2 3 μm / Si 700 μm) and SiO2 substrate (703 μm thickness) are explored here to make a comparison. If we fix the flare angle as 60 degrees and change the arm length, a linear resonant relationship is obtained as shown in Figure. 2-14(c), which can be expressed like,

\[
\frac{c_0}{f_0} = k_1 l_1 + b
\]

(2-4)

where \( k_1 \) and \( b \) are unit-less parameters, \( l_1 \) is the arm length. This provides a clear trend for adjusting resonant frequency through geometric parameters. It demonstrates that the bowtie antenna working at 10GHz also follows the dipole antenna rule of resonance.
The observation point for extracting the field enhancement factor are all chosen at 2.5 μm above the substrate in the center of feed gap. As displayed in Figure 2-14(a), most of electric field is confined within the slot PCW, which is the desired region for refractive

Figure 2-14 (a) Field enhancement distribution at x = 0 plane for feed gap region; (b) scheme of feed gap region (the areas with purple, blue and dark blue color stand for slot PCW); (c) linear resonance relationship for the two cases (SOI: k₁ = 8.339, b = 5.703; SiO₂: k₁ = 6.309, b = 1.593)
index modulation through RF incidence. This is because the doped Si with high concentration behaves more like conductor in RF frequency range that extend the bowtie arms towards the center, giving rise to a better field confinement. Moreover, for both SOI and SiO₂ substrate cases, linear resonant relationships are satisfied with the other parameters being fixed. As predicted by formula (2-1), for the same arm length, the bowtie model with higher effective permittivity substrate has lower resonance frequency and therefore higher resonance wavelength as proved by Figure. 2-14(c). Besides, the bowtie antenna with SOI substrate gives lower field enhancement. This is because the SOI substrate acts more like a perfect reflector for the RF range with a pi-phase shift upon reflection. Essentially, the silicon handle becomes a backing plane for the antenna. It causes destructive interference in the EO modulator region and significantly reduce the field enhancement factor. Therefore, without considering the fabrication accessibility, a SiO₂ substrate is preferred in our case. Bowtie antenna integrated devices on SOI substrates can be transferred as silicon nanomembranes onto glass substrates or directly fabricated on silicon-on-glass substrates to avoid impacts from backside silicon handles and to enhance their device performance.

2.8 Summary

In this chapter, based on antenna and LC circuit theory, a modified bowtie antenna model is systematically studied through numerical method. Both the effects due to high and low dielectric constants substrate have been explored, which provide improvement for bowtie-antenna-based devices through appropriate substrate. Applications of modified bowtie antenna, such like RF weak signal sensor integrated with slot PCW and silica/electro-optic polymer optical modulator for MMW receiving, have also been designed, computed, and
experimentally confirmed. By borrowing the idea of plasmonic localization in optical range, generation of confined fields with high enhancement in RF range is realized and utilized, which leads to promising hybrid devices developed from individual components in different frequency ranges.
CHAPTER 3
SLOT-ANTENNA-BASED METALLIC METASURFACE
STRUCTURES DESIGNED FOR ULTRA-LONG OPTICAL
NEEDLE FIELD WITH HIGH PURITY

3.1 Background of Optical Needle Field Generation

3.1.1 Introduction to Optical Needle Field

Generally speaking, a plane electromagnetic wave is considered to be purely transversal, hence scholars and scientists have assumed the impossibility of generating longitudinally polarized light in free space for dozens of years. Based on the result that a longitudinal field component does exist for any beam of finite diameter in free space [36], tight focusing of filtered radial polarization or hybrid cylindrical polarization are applied to create the optical field polarized in the longitudinal direction with long depth of focus (DOF) [37-40]. The generated longitudinal field, so-called optical field, tends to be a promising candidate for many applications, such as particle acceleration [36], fluorescent imaging [41], and scattering scanning near-field optical microscopy [42].

In normal cases, optical needle field generation methods are usually derived from scalar field engineering [43], which suffers from loss of generality. By introducing the vectorial
characteristic of light, a method based on reversing the radiation pattern of an electric dipole array is provided for obtaining a high purity ultra-long optical needle field [44]. The new proposed approach for obtaining longitudinal field possess uniform axial intensity profile, extended DOF as long as $8\lambda$ and longitudinal polarization with high purity. These improved properties can bring many benefits for related fields of study. For example, the optical needle field generated by the new method can offer great improvement for optical trapping technology. It ensures a uniform and elongated trapping force in longitudinal direction with increased trapping efficiency.

### 3.1.2 Calculation of Electric Field at Pupil Plane

In fact, the proposed optical needle field is equivalent to the field created by a dipole array placed in the vicinity of the focus of a high NA lens. Here, the radiation pattern of this dipole array collected by the high-NA lens in its pupil plane can be computed from the popular antenna pattern synthesis method for discrete linear dipole array [44]. Thus, by reversing the radiation of dipole array, the incident field at the pupil plane can be obtained. The schematic configuration of reversing radiation for an electric dipole array is shown in Figure. 3-1.
Here $N$ pairs of dipoles ($N=3$ in Figure. 3-1) are arranged symmetrically along the optical axis with respect to the focus; $A_n$ and $d_n$ are amplitude and spacing for the $n$th pair of dipoles; $\mathbf{e}_{\rho_0}$ represents the radial polarization direction in the local coordinate. Due to the symmetry, we only need to adjust the amplitude $A_n$, the spacing $d_n$ and additional phases $\pm \beta_n$ associated with both dipoles in each pair in order to obtain uniform longitudinal field near the focus. As written in array factor ($AF_n$), we can get formula (3-1) like,

$$AF_n = \sum_{n=1}^{N} A_n \left[ e^{i(kd_n \cos \theta + \beta_n)/2} + e^{-i(kd_n \cos \theta + \beta_n)/2} \right] .$$

(3-1)

For an objective lens that follows sine condition, the incident field can be expressed as,

$$\tilde{E}_i(\rho, \theta) = C \sin \theta / \sqrt{\cos \theta} AF_n (\cos \phi \tilde{x}_i + \sin \phi \tilde{y}_i) ,$$

(3-2)

where $(x_i, y_i)$ is the coordinate at the incident pupil plane ($P_i$); $\phi$ is the azimuthal angle in the pupil plane; $\rho_i$ is equal to $\sqrt{x_i^2 + y_i^2}$; $\theta$ is the polar angle; $C$ is the arbitrary constant.

Figure 3-1 Schematic configuration of reversing radiation for an electric dipole array (3 pairs)
For radially polarized incident beam, the radial and longitudinal electric field near focus can be expressed respectively by using the vectorial Debye theory as,

\[ E_r(r, z) = C \int_0^{\theta_{max}} AF_r(\theta) \sin^2 \theta \cos \theta J_1(kr \sin \theta) e^{ikz \cos \theta} d\theta, \quad (3-3) \]

\[ E_z(r, z) = C \int_0^{\theta_{max}} AF_z(\theta) \sin \theta J_0(kr \sin \theta) e^{ikz \cos \theta} d\theta, \quad (3-4) \]

In the proposed case, a DOF of 5\( \lambda \) with uniform intensity in the longitudinal direction around the focus has been achieved using the transparency reconstructed from an array of 2 pairs of dipoles. Here, NA = 0.95 is used for the design. Then, the parameters of the dipole array are shown in Table 1 like,

<table>
<thead>
<tr>
<th>( n )</th>
<th>( A_n )</th>
<th>( d_n )</th>
<th>( \beta_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.39( \lambda )</td>
<td>( \pi )</td>
</tr>
<tr>
<td>2</td>
<td>0.87</td>
<td>4.10( \lambda )</td>
<td>3( \pi )</td>
</tr>
</tbody>
</table>

Figure 3-2(a) and 3-2(b) display the far field intensity along and the line scan of the normalized intensity respectively. As shown in it, it is very apparent that the longitudinal field has very high purity and a nearly flat top axial distribution is located in focal volume. Therefore, the optical needle field is created near the focal volume.
In Figure 3-3, the corresponding intensity distribution in the pupil plane for the optical needle field generation is shown. We noticed that the highest transmittance occurs at the outmost ring, while the innermost rings tend to have relatively low value, which determine the length of DOF through destructive interference between different rings.

Figure 3-2 Far field intensity along focus (a) and its line scan (b)
3.1.3 Pupil Filter Discretization

The desired field at pupil plane can be considered as the transmitted field of a radially polarized electric field from a filter located at the pupil plane. The filter has a complex transmittance for both amplitude and phase [44].

In order to realize the optical needle field in practice, a discrete filter design is introduced with non-continuous transmittance and binary phase, whose structure in radial direction is shown in Figure 3-4.
As a result of the desired pupil plane filter, the electric field distributions in the transverse plane and along the z axis are illustrated as shown in Figure 3-5(a) and (b) respectively.

Obviously, this discrete filter also leads to longitudinally polarized field with extended DOF, whose distribution is very close to the continuous pupil filter case. The results in Figure 3-5 are comparable with those shown in Figure 3-2, which demonstrates that such a discrete complex pupil filter can be used as a proper substitute of the continuous pupil filter. Moreover, the discrete filter tends to be more accessible in practice based on metasurface structures.
3.2 Slot-antenna-based Metallic Metasurface Structures

3.2.1 Background of Metasurfaces

For our purpose, we need to obtain the transmitted field with different amplitude and binary phase, but same radial polarization state for each of the filter rings at the incident pupil plane. Traditionally, to realize the control of amplitude, phase and polarization state of light, fundamental optical elements, such like lenses, wave-plates and polarizers, are required in order to form a cascaded system for vectorial beam manipulation. However, none of those elements can achieve the spatial distribution modulation with desired light properties through only one integrated component. Also, SLMs may not be the potential candidates due to the bulky set-up based on it [45], which confines our choices among sub-wavelength devices.

Deep research and exploration leads us to metasurfaces as the solution for our barriers. Metasurfaces are the meta-materials in two dimensions, which are constructed with sub-wavelength metal structures of various dimensions and shapes with the ability to modulate the electromagnetic waves from microwave, infrared to visible region. With the development of new metasurfaces based on nanophotonics, phase jumps along the light path are witnessed to manipulate phase, amplitude, and eventually the polarization of light over subwavelength propagation distances [46, 47]. Composed of optical resonators specifically patterned at the interface, metasurfaces enable to engineer the local scattered field with proposed properties and eventually the overall vectorial beam, which become promising candidates for our optical needle field generation.
3.2.2 Slot-antenna-based Metasurface Structures design

Recently, multitudinous nano-scaled resonators of metasurface are proved to be effective stemmed from different design purposes. For example, by introducing a phase gradient from 0 to \(2\pi\) radians, V-shaped optical antennas were proposed and experimentally confirmed for anomalous light propagation [47]. Also, Z-shaped aperture antennas were applied in order to reach the flexible control on the spin-orbit interaction due to its symmetric geometry [48]. Moreover, with the more straightforward design and lower fabrication accessibility, the optical nanorod antennas, analogues as their RF stereotypes, have been well researched and applied in practice [49, 50]. By following the antenna scaling rules in optical range, their resonance can be easily manipulated through geometry adjustment [49]. On the other hand, based on the Babinet’s principle, slot antennas (or rectangular aperture antennas) tend to perform similar properties as their inverse counterparts, which are more suitable for Focus Ion Beam etching (FIB), giving rise to enhanced transmitted scattered field [51-53].

To further improve the scattering efficiency of rectangular slot antenna, the optimization of its geometry is necessary in order to reach the resonance condition. Physically, as a complementary structure of rod dipole antenna, slot antenna with rectangular shaped aperture in the continuous metallic film can also support dipole resonance, giving rise to the transmitted scattered field that polarized perpendicular to its long axis [54]. The signature of this dipole resonance will appear as a pronounced peak in the transmission spectrum, which is the fundamental principle for its linear polarizer applications. In order to further explore the slot antenna resonance, we applied commercial software COMSOL Multiphysics for numerical simulation. As shown in Figure. 3-6, the electric field
distribution at resonance for a single slot antenna in gold film is plotted with 1064 nm incident wavelength. The normal incident light is polarized along Y axis with the resonance wavelength of 1100nm; the slot width $a$ is chosen to be 300nm and the slot length $b$ is 60nm; the thickness of metallic layer is 100 nm, which is deposited on a glass substrate ($n_{\text{glass}} = 1.5066$); the thickness of gold film $t$ is 100nm. The dielectric data of gold is extracted from Palik's [55].

According to Figure. 3-6, the fundamental waveguide resonance mode is formed within the air gap of slot antenna. We can have an intuitive comprehension from the perspective of magnetic dipole [56]. A ring current is generated through the induced charges with opposite sign on each of the long axis sidewalls, which flows around the air gap and forms a magnetic dipole lying along X axis. As a result, the magnetic dipole mediates the coupling in the system and causes the Y-polarized scattered field to be strongly enhanced. Hence, a flexible manipulation of resonance can be satisfied by adjusting the magnetic dipole properties through changing antenna dimensions.

Nevertheless, the resonance condition of optical antenna basically differs from the one applied in RF range, which may need necessary adjustment. In RF and microwave regimes,

![Figure 3-6 Electric field distribution at resonance for the central plane of slot antenna (resonance wavelength 1100nm; slot width a 300nm; slot length b 60nm)](image)
simple rod antennas follow the ideal half-wave dipole theory under the assumption that the material is perfect electric conductor (PEC), giving rise to the rod resonance length as half of incidence wavelength [16]. Also, the resonance condition of slot antennas can be derived directly from Babinet’s principle. However, when it steps into optical range, the PEC assumption is no longer suitable, since the material loss cannot be neglected. It has been verified that the antennas tend to respond to a shorter effective wavelength $\lambda_{\text{eff}}$, which depends on the material properties [49]. In addition, as we discussed in Chapter 2, the substrate effect may also shift the resonance by changing the overall surrounding dielectric environment [51]. Therefore, an empirical formula for resonance slot width $a$ is given by counting all of these factors like,

$$a \approx \frac{\lambda_{\text{eff}}}{2n_{\text{eff}}}, \quad (3-5)$$

where $n_{\text{eff}}$ represents the effective refractive index, which lies between $n_{\text{air}}$ and $n_{\text{glass}}$. As a result, half of the resonance wavelength of a slot antenna in free space tends to be much larger than its fixed width $a$. Thus, the RF classic half-wavelength antenna theory is no longer suitable for our models in optical frequencies.
To better optimize the slot dimension in order to get desired resonance, we have simulated for the relations between slot width \( a \) and resonance wavelength by COMSOL. As displayed in Figure 3-7, the transmission spectrums for different slot widths \( a \) are obtained. The slot length \( b \) is fixed as 60nm, and the gold film thickness \( t \) is 100nm. A periodic boundary condition is applied during the numerical computation with the period of 500nm. The normal incident light is polarized perpendicular to the long axis.

![Figure 3-7](image.png)

**Figure 3-7** Transmission spectrum for slot antennas with different widths \( a \) (length \( b \) 60nm, thickness \( t \) 100nm, period 500nm)

Apparantly, the resonance wavelength depends mainly on the slot width, which can be used for resonance optimization. At the same time, the transmission increases gradually as we stretch the slot widths, since the scattered field is highly proportional to the aspect ratio of slot cross-section [54]. On the other hand, for the component polarized along long axis, its transmission coefficient is just at the order of \( 10^{-4} \), giving rise to a reliable extinction ratio for practical application. Moreover, by increasing the slot length \( b \) and metal film thickness \( t \), a blue-shift of resonance and lower transmission are also observed based on simulation.
results. Finally, by means of balancing each of the factors with reasonable consideration of fabrication ability, we choose the slot antenna dimensions like Table 3 with working wavelengths at 1064 nm and 1550 nm respectively, which are based on reachable lasers for near IR experiment set-up.

<table>
<thead>
<tr>
<th>Wavelength (λ)</th>
<th>Width (a)</th>
<th>Length (b)</th>
<th>Thickness (t)</th>
<th>Period (Λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1064</td>
<td>280</td>
<td>60</td>
<td>100</td>
<td>500/1000</td>
</tr>
<tr>
<td>1550</td>
<td>420</td>
<td>100</td>
<td>100</td>
<td>2000</td>
</tr>
</tbody>
</table>

With the local modulation like sub-wavelength linear polarizers, the metasurface based on particularly distributed slot antennas has been applied to generate orbital angular momentum carrying vector beams with broad bandwidth [57]. In our design, the scattered field generated by metasurface requires 0 and π binary phase for alternative annular rings and normalized amplitude modulated from 0.07 to 1. By cautious research and selection, we focus on the rectangular slot antennas, which behave as linear polarizers providing phase jump and amplitude modulation through their different orientations. Besides, the radial polarization state of scattered field can be reserved by properly placing the antenna direction in respect to its own local coordinate as well.

With the support of slot antennas as fundamental resonators, we are able to generate the desired radially-polarized vectorial beam with specific amplitude and phase spatial distribution. Briefly speaking, the modulation for optical properties is fulfilled through adjusting the slot antenna’s orientation in its local coordinate.
Figure 3-8 shows a single slot antenna in its local coordinate with the desired scattered field marked by the purple arrow (Figure. 3-8(a)). In this case, the slot antenna (normal direction $\hat{n}$) oriented by $\theta$ with respect to the Y axis. If the scattering efficiency $\eta$ is defined as the amplitude ratio between scattered field and incident field, then we will obtain the expression for desired scattered field like,

$$E_{\text{scat}} = \eta E_{\text{inc}} \sin \theta \cos \theta,$$

(3-6)

here we assume the component of scattered field along long axis of slot antenna to be neglected.

**Figure 3-8** Single slot antenna in local coordinate (a); multiple antennas arranged in a circle (b).

Hence, for different annular rings on the pupil mask, we can set different orientation angles to modulate both amplitude and phase, since these parameters are regarded as relative quantities. For our proposed pupil filter design expressed in Figure. 3-4, the parameters are carefully chosen as shown in Table 3,
Table 3 Design parameters for different annular rings of metasurface

<table>
<thead>
<tr>
<th>Ring Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>0.07</td>
<td>0.077</td>
<td>0.132</td>
<td>0.48</td>
<td>1</td>
</tr>
<tr>
<td>Phase (rad)</td>
<td>0</td>
<td>$\pi$</td>
<td>0</td>
<td>$\pi$</td>
<td>$\pi$</td>
</tr>
<tr>
<td>Orientation $\theta$ (deg)</td>
<td>2.0</td>
<td>92.2</td>
<td>3.8</td>
<td>104.3</td>
<td>135</td>
</tr>
</tbody>
</table>

Then, an incident light with azimuthal polarization at resonance wavelength is proposed to excite the scattered field as marked along X’ axis by the red arrow in Figure. 3-8(b). With another radial analyzer orthogonal to the azimuthal polarization, the desired scattered field (shown by purple arrow in Figure. 3-8(a)) will be kept and applied for optical needle field generation after passing through a high NA lens. After creation of the proposed vectorial field with the pattern of concentric rings, a high numerical aperture lens will be applied for tightly focusing the radial polarized components and forming longitudinal field with high purity as plotted in Figure. 3-9. Here, a three-dimensional schematic configuration is given by reserving the main functional components.

Figure 3-9 Schematic configuration for optical needle field generation system (the optical needle field is represented with purple arrows).
3.2.3 Function test experiment results and discussion

Based on the simulation results given by Table 2, the length $a$ and width $b$ of a unit rectangular slot are chosen to be 280nm and 60nm respectively to reach the resonance condition at 1064nm wavelength. After deposition of a 100nm gold film on glass substrate, the antenna slot is etched through by using Focus Ion Beam (FIB) with a period of 500nm, resulting in an overall diameter of 450µm for the whole metasurface structure. Based on the SEM image shown in Figure. 3-10, very good uniformity of the antenna in terms of direction and shape has been achieved. In case of manufacture imperfection, two metasurface structures are fabricated and tested with the same configuration. Then an incident light with azimuthal polarization at resonance wavelength is proposed to excite the scattered field as marked along X’ axis by the red arrow in Figure. 3-8(b). With another

![Figure 3-10 SEM image for metasurface sample with 450 µm diameter: (a) overall structure from top view; (b) innermost ring for the area enclosed with red dotted line in (a); (c) zoomed-in picture for the area enclosed with blue dashed line in (b).](image)

50
radial analyzer orthogonal to the azimuthal polarization (neglected in Figure. 3-9), the desired radially polarized scattered field (shown by purple arrow in Figure. 3-8(b)) will be kept and applied for optical needle field generation after passing through a high NA lens.

In order to confirm the validity of metasurface for desired vectorial field generation, we set up a characterization system for function test. The simplified schematic of the system is plotted in Figure. 3-11(c). A linearly polarized collimated light illuminates normally on the sample from the glass substrate side. The image of generated vectorial field based on metasurface sample is formed through an objective lens with NA 0.25 and magnification 10, therefore the resulted parallel optical path would allow polarizers or wave-plates placed along the propagation direction without introducing aberration. Another linear polarizer

![Figure 3-11](https://example.com/figure3-11)

**Figure 3-11** Intensity distribution for linear polarization incidence: theory (a) and experiment results for it (b); (c) schematic configuration of testing setup; (d) averaged intensity distribution within the first ring area enclosed by blue solid lines in (d) (incidence linear polarization direction is marked as white dashed line in (c)).
(LP2) with polarization direction orthogonal to the previous one is placed after the objective lens in order to filter out the incident light, while keeping the scattered light. Based on the calculation from the parameter configuration in Table 1, the intensity distribution of scattered field that determined by slot antenna orientation would be expected as a pattern of four lobes with different rotation for the five corresponding rings. Its intensity distribution is displayed in Figure. 3-11(a) with the incident polarization oriented along the white dashed line in the plot. If the incidence linear polarization direction is set as the original reference, the maximum intensity of scattered field is reached when the azimuthal angle \( \alpha \) goes to \( m\pi/4-\theta \), where \( \theta \) is the original orientation of slot antenna for each ring, and the integer \( m \) is chosen as 1, 3, 5 or 7. Therefore, the intensity distribution for different rings follows the relation like \( | \sin 2(\alpha+\theta) |^2 \). The experimental results given in Figure. 3-11(d) demonstrate a good match for slot antenna orientation between theory and experiment. The extinction ratio can be obtained as high as 250, which overly satisfies the amplitude modulation requirement of 204.

Next, another testing system for phase modulation function is necessary, since the intensity distribution based on linear polarization incidence can hardly distinguish the orientations for the rings with \( \pi \) phase difference (e.g. the first and second ring). Here, an elliptical polarized incidence light with ellipticity \( \varepsilon \) 20 degree is applied with the major axis of polarization ellipse oriented along blue dashed line as shown in Figure. 3-12(a). At the same time, a linear polarizer is placed with the polarization along the orthogonal direction of its major axis in front of the CCD in order to reduce the background light (Figure. 3-12(c)). Simply, for a linear polarizer, its Jones matrix can be expressed like,
\[ P(\alpha) = R(-\alpha) P_x R(\alpha) \]
\[ = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \Delta e^{i\delta} \end{pmatrix} \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} = \begin{pmatrix} \cos^2 \alpha + \Delta e^{i\delta} \sin^2 \alpha & \sin \alpha \cos \alpha(1-\Delta e^{i\delta}) \\ \sin \alpha \cos \alpha(1-\Delta e^{i\delta}) & \sin^2 \alpha + \Delta e^{i\delta} \cos^2 \alpha \end{pmatrix} \] (3-7)

where \( R(\alpha) \) is rotation matrix for the angle amount of \( \alpha \); \( P_x \) is the linear polarizer matrix given as,
\[ P_x = \begin{pmatrix} 1 & 0 \\ 0 & \Delta e^{i\delta} \end{pmatrix} \] (3-8)

\( \Delta \) is the amplitude ratio between the two orthogonal polarization directions, while \( \delta \) is the phase retardation. With elliptical polarization incident light, the transmitted electric field expressed in azimuthal angle \( \alpha \) can be derived like,
\[ E_{\text{out}} = P_x P(\alpha) E_{\text{in}} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos^2 \alpha + \Delta e^{i\delta} \sin^2 \alpha & \sin \alpha \cos \alpha(1-\Delta e^{i\delta}) \\ \sin \alpha \cos \alpha(1-\Delta e^{i\delta}) & \sin^2 \alpha + \Delta e^{i\delta} \cos^2 \alpha \end{pmatrix} \begin{pmatrix} \cos \varepsilon \\ i \sin \varepsilon \end{pmatrix} \]
\[ = \begin{pmatrix} 0 & 0 \\ \sin \alpha \cos \alpha(1-\Delta e^{i\delta}) & \sin^2 \alpha + \Delta e^{i\delta} \cos^2 \alpha \end{pmatrix} \begin{pmatrix} \cos \varepsilon \\ i \sin \varepsilon \end{pmatrix} \] (3-9)

For a perfect linear polarizer, we will assume \( \Delta = 0 \), and then the scattered field is like
\[ E_{\text{scat}} \propto \left[ \cos \varepsilon \sin(\alpha + \theta) \cos(\alpha + \theta) + i \sin \varepsilon \sin^2(\alpha + \theta) \right] \] (3-10)

where the original reference is defined at the major axis of incidence elliptical polarization.

Based on the theoretical calculation and experiment results (Figure. 3-12(a) and 3-12(b)), the rings with almost same scattering amplitude but \( \pi \) phase difference (e.g. the first and second rings) display alternative patterns of about 90 degree angular shift caused by the same amount of antenna orientation difference. So far, a complete confirmation for antenna
orientation and function is finished, which illustrates the desired performance as estimated. In order to do the full test based on azimuthally polarized incidence, a radial polarizer for near infrared wavelength is needed. Although the intensity of some part of rings tends to be dim (especially for the outer three rings) due to fewer slot antennas distributed within the narrower rings and fabrication imperfection, the experimentally proved design can be still used in a civility setup.

![Figure 3-12](image)

**Figure 3-12** Intensity distribution for elliptical polarization incidence: theory (a), experiment results for it (b); (c) schematic configuration of testing setup (incidence elliptical major axis direction is marked as blue dashed line in (a)).

To increase its efficiency (about 1%), a reflection type metasurface [58, 59] can be applied. That requires different types of nano-antennas, which will be demonstrated in the next chapter. Therefore, based on straightforward design of resonators and arrays, the results demonstrate the feasibility of using metasurface as a versatile tool for generating vectorial optical fields for various applications.
Based on improved slot antenna as fundamental resonators with higher efficiency, it will be more accessible to realize the optical needle field through proper experiments. The experiment set-up is shown in Figure. 3-13. Here, the spatial distribution of vectorial field as Figure. 3-4 is achieved for generating optical needle field. A near IR laser is used as illumination source at corresponding working wavelength, which is 1064 nm. Due to fabrication capability, we choose the diameter of outermost ring to be 450 µm. In order to generate the proposed excitation beam with azimuthal polarization, an experiment set-up based on few mode fiber is proposed by referring to [60]. Through a fiber coupler, the collimated laser beam is coupled into a fiber that is carefully selected so that it supports merely the fundamental mode and the second-higher-order modes. The optical fiber acts as a spatial filter and polarization mode selector. The mode coming out of the output end of fiber may happen to be a hybrid mode as plotted, hence two half wave-plates will be required to convert it into azimuthal mode. With precise alignment, the metasurface will be properly illuminated, and finally form the proposed vectorial field after filtering out the leaking incident light with radial polarizer.

![Figure 3-13 Experiment set-up for optical needle field generation](image-url)
Here a bull’s eye metallic structure plays a role as radial polarizer [61]. By considering practical fabrication capability, the bull’s eye structure is designed to have extinction ratio of over 300 with a period of 280nm and 60nm slot width according to the COMSOL simulation. By depositing a 100nm gold thin layer on glass substrate, FIB is then applied for milling the desired concentric ring structure on the film. The SEM image of the bull’s eye sample is displayed in Figure 3-14.

![Figure 3-14 SEM image of bull’s eye structure](image)

**3.3 Summary**

In this chapter, a transmission type metasurface based on subwavelength slot antennas is designed, simulated and characterized through function test experiments. By extending the traditional microwave antenna theory to infrared and optical frequency ranges, this nano-antennas-based compact device is proposed to generate ONF of $5\lambda$ DOF with flat-top
intensity. This work provides a novel approach of vectorial light modulation for amplitude, binary phase and cylindrical polarization, which paves a path of electromagnetic wave engineering by nano-antennas.
CHAPTER 4
HYBRID REFLECTION TYPE METASURFACE OF NANO-ANTENNAS DESIGNED FOR OPTICAL NEEDLE FIELD GENERATION

4.1 Introduction

In this chapter, a reflection type metal-insulator-metal (MIM) metasurface for optical needle field generation is proposed to overcome the low scattering efficiency of transmission type metasurface. It is composed of hybrid optical antennas for comprehensive spatial engineering the properties of optical fields. Still, optical needle field generation is used as an example to illustrate its capability for creating a radially polarized vectorial beam. These extraordinary capabilities for optical manipulation and modulation have been demonstrated during the development of metasurfaces. Its applications have been well investigated in the fields of anomalous reflection and refraction [47], meta-lenses [62, 63], meta-holography [64], metasurface quarter-wave-plate (QWP) [65, 66], and etc.. In the quest of miniaturization for photonic device, optical components like polarizers and QWPs in nano and micro scale can be realized through subwavelength periodic arrangement of 2D metal nano-structures. Particularly, by adjusting the geometry and periodicity of structures [65, 66], an overall retardation of π/2 can be implemented, giving
rise to broadband meta-waveplates based on interleaved nano-rod antennas or V-antennas. Besides, with the use of metal-insulator-metal (MIM) structure, the scattering efficiency of reflection type meta-waveplates can be further improved without sacrificing the desired manipulation capability [59, 67]. Hence, in order to obtain high power reflection light, the MIM meta-waveplates can be designed as segmented QWPs to generate radially polarized light with phase and amplitude modulations. The generated vectorial optical field finds wide applications, including the creation of an optical needle field (ONF) under high numerical aperture (NA) focusing [37]. The so-called ONF is substantially polarized along the longitudinal direction with long depth of focus and formed through the focusing of filtered radial polarization [39, 40, 44, 68]. It has attracted a large amount of interests as a promising candidate in polarization sensitive orientation imaging [41], particle manipulation [69] and so on. Although numerical simulations have shown that an optical needle of about $14\lambda$ in length with homogeneous intensity along the optical axis is feasible based on focusing of hybridly polarized vector beam [38], the experimental realization is still challenging owing to the pixel size of available spatial light modulator (SLM) and its limited amplitude modulation capability. In addition, the SLMs are bulky and expensive, making them difficult to integrate with existing optical microscopes, hampering the use of such exotic optical fields in many applications. Therefore, the availability of low cost and compact device that allows the easy generation of the required pupil illumination for the ONF generation is highly attractive.

As mentioned before, based on the method of reversing the electric dipole array radiation, discrete complex pupil filter has been designed as an approximation of a continuous filter for easier implementation in order to form the desired incident field for ONF generation
This complex filter gives rise to spatial polarization, phase as well as amplitude modulations to the input optical illumination. Such a discrete design is ideal for the implementation with MIM metasurfaces. By applying MIM metasurfaces to implement this discrete complex pupil filter, the desired complex field with radial polarization can be created and focused by a high NA lens to generate the ONF. In this chapter, a hybrid reflection type MIM metasurface composed of different types of nano-antennas is demonstrated to create a radially polarized vectorial beam with full control capability, which can be applied specifically in ONF generation as an example. Functioning as local QWP, MIM metasurface is designed to convert incident circular polarization without geometric phase term into local linear polarization to create an overall radial polarization with corresponding binary phases and desired normalized amplitude ranged from 0.071 to 1 [44]. In this design, periodic arrangements of double metallic nano-bars with perpendicular placement and single nano-bars are carefully engineered for different modulation requirements respectively, while maintaining $\pi/2$ retardation. The overall hybrid metasurface structures compound several functions within one device, leading to a compact device for vector beam engineering that may provide highly desirable solutions for optical integration.

4.2 Design of discrete complex reflection modulator for ONF generation

To obtain the desired complex field for ONF generation, a method based on reversing the radiation pattern of an electric dipole has been developed [44]. Owing to the vectorial characteristics of the illumination, a high purity and ultra-long ONF can be realized. The proposed approach for obtaining longitudinal field possesses uniform axial intensity profile, extended DOF as long as $8\lambda$ and longitudinal polarization with high purity. Based on this
method, a discrete modulator with non-continuous complex reflectance and binary phase in order to realize the ONF is designed. To simplify the complexity of fabrication and design, a device with five modulation rings is proposed that can generate an ONF with the DOF of $5\lambda$. The normalized amplitude of its modulated reflectance in radial direction is shown in Figure 4-1 (a).

The parameters of five rings marked by corresponding numbers are displayed in Figure 4-1 (a). The radially polarized light formed by Ring #4 and #5 play major roles in forming longitudinal polarization of the ONF [68], while the length of DOF depends mainly on the configurations of the first three rings. Besides, Ring #1 and #3 require $\pi$ phase jump comparing with the other rings, giving rise to balanced contributions to extended DOF. The Regions #0 are actually undesired dark areas with zero reflection, from which the light needs to be totally absorbed or deflected. Hence, the desired output light for ONF generation can be obtained, whose parameters listed in Table 4. After the modulated radial polarization light passing through a high NA lens (NA = 0.95), a longitudinally polarized light at focus is expected with a flat-top intensity of $5\lambda$ DOF as plotted in Figure 1(b).
Therefore, to realize the discrete complex reflection modulator, we focus on the design of practical reflection metasurfaces with specific nano-antennas that enable us to comprehensively engineer vectorial light with maximal flexibility.

Table 4 Parameters of discrete complex reflection modulator design

<table>
<thead>
<tr>
<th>Ring #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>0.071</td>
<td>0.145</td>
<td>0.133</td>
<td>0.478</td>
<td>1</td>
</tr>
<tr>
<td>Phase</td>
<td>0</td>
<td>π</td>
<td>0</td>
<td>π</td>
<td>π</td>
</tr>
<tr>
<td>Widths</td>
<td>0.105</td>
<td>0.065</td>
<td>0.13</td>
<td>0.05</td>
<td>0.055</td>
</tr>
</tbody>
</table>

4.3 Design of discrete complex reflection modulator for ONF generation

4.3.1 Design of MIM nano-bars structures

As one of the innovative field of metamaterials developed recently, reflection type metasurfaces have become a promising candidate for novel optical manipulation with its high efficiency and broadband performance [58, 67]. With MIM configuration of a nanoscaled spacer layer being sandwiched by upper metallic arrays and bottom mirror, the gap plasmon resonance can be facilitated for reflection light control based on cautious adjustment for structure dimensions [70, 71]. As the simplest structure, metallic nano-bar is chosen to be the unit cell of upper antenna layer for the realization of π/2 retardation with high conversion efficiency as demonstrated in [71]. In this work, a broadband reflection coefficient of about 90% can be reached with the support of nano-bar MIM antenna, which may satisfy the highest requirement of reflection amplitude for our design. However, the
structures with more degrees of freedom are still needed in order to cover the normalized amplitude range from 0.071 to 1 for the reflected light.

To meet these demands for modulation accessibility, a metasurface based on interleaved gold nano-bars are taken into cautious considerations for our purpose. As the simplest electric dipole scattering structure, the resonance of a single metallic nano-bar can be tailored through geometry adjustment in order to obtain reflection amplitude over 80% and desired phase for scattered field. In this design, the nano-bars are periodically deposited on a glass thin layer with a gold optically thick bottom layer, giving rise to the MIM structures, so-called continuous-layer gap plasmon resonators [72]. For each of the unit cells, the resonator basically performs either as a magnetic dipole that is formed by electric currents flowing through upper metallic bar and bottom layer or an electric dipole depending on resonance conditions. With proper choice of unit cell dimensions, the gap plasmon resonance can be obtained, resulting in minimum reflection due to most of energy being stored within the glass spacer region. From this point, the structures enable to function either as on-resonance perfect absorbers or off-resonance reflective components depending on geometric adjustment. Furthermore, if two orthogonal arrays of nano-bars are interleaved with each other, a desired reflection phase difference can be engineered by keeping one array of nano-bars above resonance and the other below resonance respectively. Particularly, by perpendicularly positioning two arrays of nano-bars with a proper nano spacing for coupling purposes, the $\pi/2$ phase retardation can be reached with each of the nano-bars corresponding to orthogonal polarizations [66, 73]. With considerable numbers of degrees of freedom these interleaved nano-bars MIM structures
are supposed to cover our amplitude modulation range and maintain the phase retardation, which are promising for the full control of optical properties.

In Figure 4-2(a), the schematic plot for the unit cell of orthogonally patterned nano-bars MIM structures is illustrated. The unit cell is extracted from a rectangular lattice with the subwavelength periods of $\Lambda_x$ and $\Lambda_y$ along X and Y directions respectively. A glass spacer layer with the thickness of $t_s$ is sandwiched by an antenna layer composed of gold nano-bars array and bottom layer. The thickness of bottom layer $t_b$ is chosen to be over 80 nm.

Figure 4-2 Schematic plot for (a) orthogonally patterned MIM double nano-bars unit cell; (b) MIM single nano-bar unit cell.
which is much greater than the penetration depth of gold and can be considered as a perfect reflector at the working wavelength 1064 nm. The two nano-bars are placed perpendicularly along their corresponding axes respectively with a separation gap of \( g \), giving rise to an overall symmetric “T” shape. By balancing between the effective coupling distance and fabrication capability, the separation gap \( g \) is chosen to be 10 nm. The lengths and widths of nano-bars are expressed by \( a_i \) and \( b_i \) \((i = 1, 2)\) as shown in the plot, which requires systematic exploration for resonance in order to pursue the desired reflection field. On the other hand, the unit cell of MIM single nano-bar is displayed in Figure 4-2(b). Deposited on the same glass spacer layer, the single nano-bar thickness is also chosen to be \( t_b \) as the double bars structures’ with the length and width being expressed by \( a_3 \) and \( b_3 \) respectively.

Particularly, we split each of rings into 32 uniform center-symmetric sectors composed of corresponding nano structures as shown in Figure 4-3. In one specific ring, each of the 32 sectors has the same configurations of nano-antenna periodic arrangement. In this case, we can investigate the scattered field in the local rectangular coordinate of the sector region \((X', Y')\), where \( X' \) and \( Y' \) are actually along the azimuthal and radial directions of the ring respectively. To obtain an overall radial polarization output, the rotation for the rectangular two-dimensional array is required in order to achieve an output linear polarization locally along \( Y' \) axis (Figure 4-3(c)). Under normal incident circular polarization illumination, the output Jones vector \( J_{\text{out}} \) can be expressed as,
\[ J_{\text{out}} = M_{\text{RM}}J_{\text{in}} = R_{\text{mirror}} R(\theta) M R(\theta) J_{\text{in}} \]
\[ = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} e^{i\phi_r} \begin{pmatrix} r_x & 0 \\ 0 & r_x e^{i\Delta \phi} \end{pmatrix} \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \]
\[ = \frac{e^{i\phi_r}}{\sqrt{2}} \left( \begin{array}{c} r_x \cos^2 \theta + r_x \sin^2 \theta e^{i\Delta \phi} + i r_x \cos \theta \sin \theta - i r_x \cos \theta \sin \theta e^{i\Delta \phi} \\ -r_x \cos \theta \sin \theta + r_x \cos \theta \sin \theta e^{i\Delta \phi} - i r_x \sin^2 \theta - i r_x \cos^2 \theta e^{i\Delta \phi} \end{array} \right) \]

(4-1)

Here, \( J_{\text{in}} \) is the normalized circular polarization input; \( M_{\text{RM}} \) is the Jones matrix representation of reflection metasurface; \( R_{\text{mirror}} \) is the reflection factor; \( R(\theta) \) is the rotation matrix with the angular amount of \( \theta \); the retardation is expressed as \( \Delta \phi = \phi_y - \phi_x \), which is the difference between the reflectance phase of Y and X axis; the amplitude of reflectance \( |r| \) is expressed by \( r_x \) and \( r_y \), the reflectance amplitude along Y axis and X axis, like \( |r| = \sqrt{|r_x|^2 + |r_y|^2} \); \( \alpha \) is the angle intersected between X axis and output linear polarization direction expressed as \( \tan \alpha = r_y / r_x \). With specific structure design, the retardation \( \Delta \phi \) can be fixed as \( \pm \pi / 2 \), and a QWP function is realized. The final output Jones vector is like,
\[ J_{out} = \frac{e^{j\phi}}{2 |r|} \left( \begin{array}{c} r_x \cos^2 \theta \pm r_y \cos \theta \sin \theta \pm ir_y \sin^2 \theta \cos \theta \sin \theta \\ -r_x \cos \theta \sin \theta \pm r_y \cos^2 \theta \pm ir_y \cos \theta \sin \theta - ir_y \sin^2 \theta \end{array} \right) \]

Therefore, when \( \Delta \phi = \pi/2 \), let \( \theta = \pi/2 + \alpha \), then we have

\[ J_{out} = \frac{e^{j\phi'}}{2 |r|} \left( \begin{array}{c} 0 \\ -\frac{1}{\cos \alpha} \end{array} \right) = \frac{e^{j\phi'}}{2 |r|} \left( \begin{array}{c} 0 \\ -\frac{1}{\cos \alpha} \end{array} \right) \] (4-3)

where \( \phi' = \phi + \alpha \pi/2 \). On the other hand, when \( \Delta \phi = -\pi/2 \), let \( \theta = \pi/2 - \alpha \), then

\[ J_{out} = \frac{e^{j\phi''}}{2 |r|} \left( \begin{array}{c} 0 \\ -\frac{1}{\cos \alpha} \end{array} \right) = \frac{e^{j\phi''}}{2 |r|} \left( \begin{array}{c} 0 \\ -\frac{1}{\cos \alpha} \end{array} \right) \] (4-4)

where \( \phi'' = \phi - \alpha \pi/2 \). Here, \( \phi' \) and \( \phi'' \) are modulated reflection phase along X axis, which need to be chosen as binary phases based on Table 1 for different rings.

### 4.3.2 3D modelling and analysis

To meet the modulation requirement of MIM metasurface, we investigate the geometric parameters for the structures systematically. In our design, the 3D modelling and numerical simulation for unit cell is accomplished by applying a commercial finite element method (FEM) software (COMSOL Multi-physics). The permittivity of materials is extracted from Palik’s [55]. Under periodic boundary conditions, the nano-bar antenna is illuminated by normal incident light with X and Y polarization respectively. Then, the complex reflected field is collected at the input port for further analysis.

Firstly, the thickness configuration requires optimization for minimum reflection, while the other system parameters are fixed as constants \( A_x = A_y = 260\text{nm}, b_1 = b_2 = 25\text{nm}, \).

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$a_1=145\text{nm}, \ a_2=135\text{nm})$. In this case, the MIM structure behaves similarly to the well-known metamaterial perfect absorber [74], whose resonance condition can be reached based on the transmission line theory. This theory is borrowed from LC circuit design that can realize lowest reflection by satisfying the impedance matching to free space. As a result, given by the 2D mapping of reflectance as a function of thicknesses, the minimum reflection amplitude $|r|$ of 0.166 is obtained when $t_m = 20\text{nm}$ and $t_s = 55\text{nm}$, which are still within the fabrication capability of modern nanofabrication tools. Then based on this thickness configuration, we focus on deeper optimization through the adjustment of unit cell period. For Ring #1, an asymmetric rectangular lattice ($\Lambda_x = 330\text{nm}, \ \Lambda_y = 250\text{nm}$) is used to reach the resonance conditions for both directions respectively. Under on-resonance state, a reflection amplitude $|r|$ as low as 0.056 can be reached based on proper choice of nano-bars dimension as shown in Figure 4-4(a). If we slightly change the current parameters, one of the nano-bars can be shifted above resonance, while the other below resonance. This gives rise to the possibility of flexible control for phase difference. With appropriate amount of shift, two retardation contours for $-\pi/2$ (black) and $\pi/2$ (white) can be found as represented by the dotted lines. By searching parametric combinations along these contours in both Figure 4-4(a) and 4-4(d), the requirements for both amplitude and phase can be satisfied while maintaining the QWP funtion. After cautious considerations, a double nano-bar unit cell with $a_1 = 146.4\text{ nm}, \ a_2 = 139.2\text{ nm}, \ b_1 = b_2 = 25\text{nm}$ is selected to achieve a reflection amplitude $|r|$ of 0.0585 and a modified reflectance phase $\phi_x$ of 0 rad. Also, the rectangular lattice needs a counterclockwise rotation with the amount $\theta$ of 159.1 degrees ($\theta = \pi/2 + \alpha = 90\text{ deg} + 69.1\text{ deg}$) for aligning the output linear polarization to the radial direction in the laboratory coordinates.
Figure 4-4 2D mapping plots for MIM metasurface Ring #1 ($\Lambda_x =330\text{nm}$, $\Lambda_y = 250\text{nm}$, $b_1 = b_2 = 25\text{nm}$) (a) the amplitude of reflection $|r|$; (b) phase retardation $\Delta\phi$; (c) output linear polarization angle $\alpha$; (d) modulated reflection phase $\phi'$. 
For further insight of gap plasmon resonance, we analyze the modes of double nano-bars structures with different bar lengths as shown in Figure 4-5. At Y = 0 plane, the 2D electric field enhancement mappings are given for both off and on resonance states. Here the electric field enhancement (FE) is defined as the ratio between the amplitudes of observed electric field and incident electric field. Flowing through the nano-bars and bottom layer, out-of-phase currents are formed in Figure 4-5(a), which is a typical magnetic dipole response [72]. Derived from a closed loop of electric currents, it is actually a magnetic

![Figure 4-5](image-url) 2D distributions of electric field enhancement and current density arrows for double nano-bars structure (a) Off-resonance state ($a_1 = 135$ nm, $a_2 = 130$ nm); (b) On-resonance state ($a_1 = 145$ nm, $a_2 = 140$ nm).
analogue of electric dipole that brings about a maximum scattering cross section. Hence, most of the power is reflected back due to the domination of scattering effect, giving rise to an overall reflective device under off-resonance state. On the other hand, when the resonance is on (Figure 4-5(b)), the electric dipole response dominates the structure’s performance with higher enhanced electric field being generated around the nano-bars. In this case, a major function of absorption is expected, since the MIM structures have stored most of the power within its near field region. Therefore, with the support of resonance control, it enables to switch the roles of MIM resonator between reflector and absorber, which covers the normalized amplitude range from 0.071 to 0.478 for the first four rings by adjusting the dimensions of double nano-bars.

Moreover, in the case of Ring #5, the unit cell of MIM single nano-bar is chosen due to its relatively high reflection and straightforward geometry. Through similar design procedures, we manipulate the optical performance of its square array with 190 nm period (Figure 4-2(b)). A segmented reflective QWP is desired as marked with the outermost ring in Figure 4-3(a).

Figure 4-6 illustrates the 2D mapping plots for MIM metasurface Ring #5. When the dimension of unit cell nano-bar is chosen as $a_3 = 141$ nm, $b_3 = 123.3$ nm, the reflection amplitude $|r|$ can be reached as high as 0.826 with a modified reflection phase $\phi_x''$ of $\pi$ rad. In summary, Table 5 lists all of the geometric configurations for the five segmented QWP rings, which satisfy all the modulation requirements.
Figure 4-6 2D mapping plots for MIM metasurface Ring #5 ($\Lambda_x = \Lambda_y = 190$nm) (a) the reflection amplitude $|r|$; (b) phase retardation $\Delta\phi$; (c) output linear polarization angle $\alpha$; (d) modulated reflection phase $\phi^\prime$. (The dotted lines represent the retardation contour for $-\pi/2$ (black) and $\pi/2$ (white) respectively.)
Table 5 MIM metasurface structures parametric configurations

<table>
<thead>
<tr>
<th>Ring #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection Amplitude $</td>
<td>r</td>
<td>$</td>
<td>0.0585</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>Normalized Amplitude</td>
<td>0.071</td>
<td>0.145</td>
<td>0.133</td>
<td>0.478</td>
<td>1</td>
</tr>
<tr>
<td>Phase (rad)</td>
<td>0</td>
<td>π</td>
<td>0</td>
<td>π</td>
<td>π</td>
</tr>
<tr>
<td>Geometry $(a_1, a_2)$</td>
<td>(146.4, 139.2)</td>
<td>(134.9, 127.4)</td>
<td>(145.3, 141.8)</td>
<td>(154.8, 153.0)</td>
<td>$(a_3, b_3) = (141.0, 123.3)$</td>
</tr>
<tr>
<td>$(b_1, b_2)$ (nm)</td>
<td>(25, 25)</td>
<td>(20, 20)</td>
<td>(25, 25)</td>
<td>(45, 45)</td>
<td></td>
</tr>
<tr>
<td>Period $(\Lambda_x, \Lambda_y)$ (nm)</td>
<td>(330, 250)</td>
<td>(240, 230)</td>
<td>(330, 260)</td>
<td>(330, 250)</td>
<td>(190, 190)</td>
</tr>
<tr>
<td>Output LP angle $\alpha$ (deg)</td>
<td>69.1</td>
<td>3.7</td>
<td>30.0</td>
<td>50.4</td>
<td>43.2</td>
</tr>
<tr>
<td>Rotation angle $\theta$ (deg)</td>
<td>159.1</td>
<td>86.3</td>
<td>60.0</td>
<td>140.4</td>
<td>46.8</td>
</tr>
</tbody>
</table>

4.3.3 MIM disk structures

To eliminate the undesired reflection light within Regions #0 (Figure 4-3(a)), a MIM disk metasurface with the same thickness configuration is applied in order to deflect the incident circular polarization light off normal direction. Since the disk shape is supposed to be
polarization-independent, it enables to work for circular polarization input in our case. With the square period fixed as 260 nm for each of sub-units, the reflection phases for different disk diameters are simulated based on 3D modelling. As displayed in Figure 4-7(d), five gradual phases for different diameters with a step of $0.4\pi$ rad are extracted to cover a full wave with 1064 nm wavelength (Table 6).

**Table 6 Reflection phases of the chosen disk diameters**

<table>
<thead>
<tr>
<th>Diameters (nm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>76</td>
<td>168</td>
<td>186</td>
<td>204</td>
<td>250</td>
</tr>
<tr>
<td>Phase ($\pi$ rad)</td>
<td>0.91</td>
<td>0.51</td>
<td>0.11</td>
<td>-0.29</td>
<td>-0.69</td>
</tr>
</tbody>
</table>

By placing these 5 sub-units of MIM disk structures in line along X axis, we obtain a super-periodic array ($5\Lambda_x \times \Lambda_y$) that provides an anomalous reflection effect for deflection application (Figure 4-7(a) and 4-7(b)). The deflection angle $\theta_d$ can be expressed as [47],

$$\theta_d = \arcsin \left( \frac{\lambda}{2\pi} \frac{d\phi}{dx} \right) = \arcsin \left( \frac{\lambda}{2\pi} \frac{0.4\pi}{\Lambda_y} \right) = \arcsin \left( \frac{1064\text{nm}}{5 \times 260\text{nm}} \right) = 54.9\text{deg} \quad (4-5)$$

Furthermore, without loss of generality, we have simulated the deflection performance with Y polarized incident light for the narrowest part in our design (the region between Ring #3 and #4), which contains merely 5 super-periods along X axis as shown in Figure 4-7(c). The light blue arrows represent the relative power flow given by the scattered field, whose lengths illustrate the power flow amplitude in logarithmic scale. By calculating from the figure, most of power is deflected by the amount of 54.6 degree.
Apparently, a higher diffraction efficiency is expected if more super-periods are added, resulting in a deflection angle closer to the theoretic estimation in (4-5) as well. To check the completeness of our model, the same structures are illuminated with X polarized incident light. At this time, $\theta_d$ is simulated as 55.4 degree, which is still acceptable for us, since the main purpose is to eliminate undesired light only. Hence, with engineered super-periodic disk MIM structures filled in the dark regions, we realize nearly-zero reflection in normal direction for Regions #0. So far, a hybrid MIM metasurface has been proposed based on 3D FEM modelling with proper choice of three characteristic optical antennas working at near IR wavelength.

![Figure 4-7](image-url)

Figure 4-7 (a) MIM disk structures unit cell; (b) deflection behavior of MIM disk array; (c) scattered electric field distribution for 5 super-periods of unit cell with Y polarized incident light (the relative power flow is marked with light blue arrows); (d) Disk diameter vs. reflection phase (the chosen diameters are marked with red dots).
4.3.4 Proposed experimental configuration

For the practical purpose, we propose a schematic set up as shown in Figure 4-8. The MIM metasurface sample is illuminated by a normal circular polarization light at the wavelength of 1064 nm after passing through a spiral phase plate to eliminate its intrinsic geometric phase term. After vectorial light modulation by metasurface, the polarization stable beam splitter will reflect the desired scattered field to the CCD camera for observation. The patterned radially polarization output can be further tightly focused by a high NA lens (NA=0.95) for ONF generation.

Figure 4-8 Schematic plot for proposed experimental configurations
4.4 Summary

In summary, a hybrid reflection type MIM metasurface of nano-antennas at near IR wavelength is designed, modelled and proved numerically for vectorial light engineering. Functioning as a segmented QWPs, the designed structure convert the circular polarization incident light to radially polarized complex field with specific spatial polarization, phase and amplitude modulations. With the help of MIM double and single nano-bars resonators, the modulation for normalized reflection amplitude can cover a range from 0.071 to 1 with a binary phase control as well. The gap plasmon resonance derived from the structures is controlled through antenna dimensions for the realization of desired optical performance. A device that can create the required complex field for the generation of an ONF with a flat-top intensity of $5\lambda$ DOF is demonstrated as an example. The proposed MIM metasurface will provide promising possibilities for a new class of compact components based on nano-scaled structures that realize compound functions for vectorial light generation.
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

As promising candidates for engineering EMW properties, subwavelength antennas are discussed in details from RF to IR and optical frequency range. Exciting results have been obtained, which illustrate the capabilities of RF broadband field enhancement generation and subwavelength-antenna-based metasurface full wave modulation for amplitude, binary phase, polarization and retardation. Due to the subwavelength size of antennas, MMW engineering and optical properties’ manipulation are realized with compact micro-devices, which can definitely bring innovations for next-generation electro-optics components. Besides, systematic exploration for different antenna structures are also given, which can meet specific design purposes, such as high field enhancement with broad bandwidth, vectorial light polarization control, light deflection independent with polarization and full wave properties manipulation.

As the future work, the experimental realization of optical needle field needs to be achieved from the focusing of desired vectorial light. Also, fabrication and experimental characterization work for reflection type hybrid metasurface structure is required in order to increase the scattering efficiency further.
BIBLIOGRAPHY


VITA

Shiyi Wang was born on July 6th, 1985 in Harbin, Heilongjiang Province, People’s Republic of China, the son of Zhigang Wang and Fengmei Jiang. After completing his high school at Harbin No. 3 Middle School, he entered Harbin Institute of Technology for undergraduate study majored in Physics in 2004. He graduated in 2008 with a bachelor’s degree and continued his master study in the same university. He obtained his master degree in Optics from Harbin Institute of Technology in 2010. After that, he came to the Electro-Optics program at the University of Dayton for doctoral study. He obtained his PhD in Electro-optics in 2015. His research is focused on the engineering of electromagnetic wave based on subwavelength antennas.