Micromachined tunable metamaterials for terahertz application

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**NANYANG
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**MICROMACHINED TUNABLE METAMATERIALS
FOR TERAHERTZ APPLICATION**

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ENGINEERING
2015**

MICROMACHINED TUNABLE METAMATERIALS FOR TERAHERTZ APPLICATION

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Zhang Wu

SUMMARY

The metamaterial realizes novel optical properties through artificially designed metamolecules. Advanced to the natural materials, the permittivity and permeability of the metamaterial can be flexibly designed for different optical responses. The optical response can be effectively controlled through various approaches which enables metamaterials' practical applications in many areas. This doctorate thesis focuses on the design, fabrication and experiment of reconfigurable metamaterials for THz wave control and modulation using the micromachined fabrication technique. Specifically, the optical responses of the metamaterial are tuned in three aspects, i.e. the magnetic response, the electric response and the optical activity.

The first part of the thesis reports a magnetic response control through a reconfigurable metamaterial. The magnetic response is induced in a planar metamaterial under oblique incidence. The couplings in the metamolecule are changed by reconfiguring the metamolecule structure that is driven by micromachined actuators. The reflection intensity at the magnetic resonant frequency is effectively tuned.

The second part of the thesis focuses on the electric response tunable metamaterial in THz spectrum. A metamaterial consisting of both radiative structure and non-radiative structure are designed. The electric response of the metamolecule is actively tailored by changing the destructive coupling effect, or the EIT-like effect between the two kinds of elements. The reflection is tuned through the coupling change of the two elements. In addition, the electric response tuning is also realized in a metamaterial with separated metallic structures. The distance between the two elements can be changed and the capacitive couplings are tuned. A conductive coupling is also

induced by contacting the separated metal structures through the reconfiguration. The transmission of the metamaterial is significantly changed through the capacitive and conductive tuning and switching.

The third part of the thesis is on a metamaterial for tunable optical activity in THz regime. Two different metamaterials are proposed for the optical activity realization. A planar metamaterial which manifests extrinsic chirality is proposed. Significant optical activity is observed in this design under an oblique incidence. The polarization rotation is reversed by tuning the chiral structure to its enantiomer shape. A semi-3D chiral structure is also designed in which a planar chiral pattern is collapsed into a semi-3D architecture. Intrinsic chirality is realized while the structure is still in single layer. Strong optical activity is derived through the coupling between electric field and magnetic field in the stereo structure and is changed at different structure geometric size.

In conclusions, tunabilities on the magnetic resonance, the electric resonance and the optical activity in THz wave are realized through the metamaterial reconfiguration, which have high potential applications in optical filter, switch and polarization rotator, etc.

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NOMENCLATURE

THz	Terahertz
EM	Electromagnetic
SRR	Split-Ring Resonator
EIT	Electromagnetically induced transparency
ENZ	ϵ -near-zero
PCB	Print Circuit Board
NIL	Nanoimprint Lithography
YIG	Yttrium Iron Garnet
YBCO	Yttrium Barium Copper Oxide
PDMS	Polydimethylsiloxane
MEMS	Microelectromechanical Systems
CST	Computer Simulation Technology
FP	Fabry-Pérot
FSR	Free Spectra Range
FTIR	Fourier transform infrared spectroscopy

CHAPTER 1

INTRODUCTION

1.1 Motivation

The PhD research topic is motivated by the potential of effective control and manipulation of the terahertz (THz) wave through micromachined reconfigurable metamaterials using silicon deep etching fabrication processes. The development of the reconfigurable metamaterial offers large opportunity to actively modulate THz wave for real life applications, which is hardly obtained from natural materials. Specifically, the metamaterial has made a great reputation on the substantial control of EM waves in the fields of wave diffraction, energy absorption, polarization state and nonlinear properties, etc.

The metamaterial refers to an artificial material which has come to research attention since the beginning of last decade. Similar with natural materials which interact with EM wave through large amounts of atoms or molecules, the metamaterial responds to the EM wave through some artificially structured metamolecules [1]. In fact, the manipulation of light with structured material has been widely observed in nature and also realized in artificial works for a long time. For example, a Morpho rhetenor butterfly shows strong iridescence through photonic structured multilayers on its wings [2]. While as a work of art, the Lycurgus Cup

shows different illuminations under different incident conditions due to the interactions between the light and the nanoparticles in the glass [3]. These optical phenomena have attracted the interests of scientists for centuries and plenty of mysteries of light have been recovered such as optical diffraction, interference and dispersion. Later in nineteenth century, the development of EM theory pushed the light research to a new level and the interactions between materials and light are intensively studied.

The applications of optical devices are exploded in the area of communication, detection, imaging, data storage and solar energy, etc. Various optical designs and materials are also proposed such as Bragg gratings[4], photonic crystals [5] and plasmonics [6]. The metamaterial, a new rising field of the structured material for light control, interacts with both electric field and magnetic field of the EM wave and thus manipulates the EM waves more effectively.

In natural materials, the optical properties are depending on the intrinsic permittivity ε and permeability μ of the material, the values of which are constrained by the atoms or molecules in the material. On the contrary, the metamaterial's permittivity and permeability, which depends on the artificial structures and scales of the metamolecules, are specifically designable for different optical properties and applications. Therefore, the metamaterial has a large advantage over the natural material when applied the fields requiring special optical responses. For example, the metamaterial can be designed with an optimized permittivity and permeability tensors to control the propagation direction of EM wave and absorption in the material, which has large potentials for the realization of optical cloaking [7]. The

metamaterial also plays important role on the evanescent wave enhancement through its unique properties [8]. The subwavelength imaging, which is theoretically limited in natural materials, becomes possible through evanescent wave enhancement in the metamaterial and explores a paradise for the area of detection, sensing and imaging [9], etc. In addition, the metamaterial also realizes strong optical activity which are extremely weak in nature [10, 11] while has large potentials to be applied for communication, data storage and biological study, etc.

The realization of metamaterial, which acquires its optical properties through subwavelength metamolecules, is much benefit from different fabrication technologies [12]. For the response from GHz frequency to optical visible regime, the corresponding metamolecules' size ranges from millimeter to nanometer. These metamolecules can be realized through the matured fabrication technique. In addition, based on current micromachined actuator technology, various tunable metamaterials can be developed to cater to different applications.

The optical properties of the metamaterial are realized through strong optical resonance in the metamolecules [13]. The resonant band is usually quite narrow and therefore the metamaterial only works in a limited optical spectrum band, being one of the main limitations of the metamaterial. One promising solution to this problem is to use a metamaterial with tunable resonances, which can be shifted to different frequencies [14]. The tunable resonance can also be used to control the resonant strength by realizing a tunable permittivity and permeability. As the metamaterial optical properties largely depends on the metamolecule structures, it can be concluded that the reconfiguration of the metamolecule can substantially change

metamaterial's responses to the EM wave, including electric response, magnetic response and electromagnetic couplings, ect [15].

1.2 Objectives

The main objective of this research is to (1) investigate different optical resonance and related optical properties in the tunable metamaterial; (2) develop and demonstrate a reconfigurable metamaterial for active control and manipulation of the optical responses. The electric resonance, the magnetic resonance and the optical activity induced in metamaterials are to be investigated at different reconfigured elements and different incident conditions through both numerical calculation and theoretical modeling methods.

The tunability of optical responses is to be demonstrated in THz regime in different types of metamaterials: the magnetic response tunable metamaterials, the electric response tunable metamaterials and the optical activity tunable metamaterials. The tuning on the resonant frequency, the resonant strength and the coupling effect in the metamolecule are investigated, which controls the transmission, reflection and the polarization state of the THz wave.

The micromachined fabrication processes are developed for the reconfigurable metamaterial realization. The structures of the metamolecules are reshaped and the changing of the optical responses are controlled by micromachined actuators. Different optical functions of the tunable metamaterials are then demonstrated and experimented.

1.3 Major contributions

The major contributions of this PhD thesis lie in various aspects of the theoretical analysis, designs, fabrications and experiments of three different reconfigurable metamaterials. The details are listed below:

- 1) A new approach for control of EM wave are proposed which reconfigures the metamaterial. Optical responses in THz regime are effectively tuned through the reconfiguration. The reconfigurable metamaterial provides a new paradigm for dynamical control on the EM wave.
- 2) The micromachined fabrication processes are developed for the realization of the reconfigurable metamaterials. The tunability is substantially demonstrated on different optical responses.
- 3) The magnetic response in a properly designed metamaterial is effectively tuned in THz regime. Theoretical modeling and numerical calculations are applied to investigate the tuning mechanism. The magnetic response is enhanced through metamolecule structure optimization and the resonant strength tuning are experimentally demonstrated through metamolecule reconfiguration. (See Chapter 3)
- 4) The electric response in a properly designed metamaterial is significantly tuned in THz regime. The tunability by changing destructive coupling, capacitive coupling and conductive coupling effect are numerically calculated, and its theoretical model is developed for the coupling analysis in the metamolecules.

The transmission and reflection are significantly tuned and switched through the electric response control. (See Chapter 4)

- 5) A strong optical activity is obtained through a planar metamaterial with extrinsic chirality. Numerical results on the circular birefringence and the circular dichroism are investigated in different light incident conditions. The polarization rotation through the planar chiral metamaterial is reversed by reconfiguring the chiral metamolecule to its enantiomers shape. (See Chapter 5)
- 6) A semi-3D metamaterial with intrinsic chirality is innovated. The theoretical analysis and numerical calculations indicate a giant optical activity through metamaterial, which is experimentally demonstrated. A simplified fabrication process is developed for the semi-3D metamaterial. The optical activity is changed at different metamolecule geometry. (See Chapter 5)

1.4 Organization of the thesis

The thesis consists of six chapters. The first chapter of the thesis presents the motivation, objective, and major contributions. The motivation section explains the background of the research work and how the background inspires the PhD project. The objective section clarifies the purpose of the research and the contribution section summarizes the innovations, design, simulation, theoretical analysis and fabrication processes development.

In Chapter 2, literatures on the developments of metamaterials are reviewed. This chapter reviews physical principles in the metamaterial and some related novel optical properties rarely found in nature. Different applications of metamaterials are briefly summarized. The research background of THz metamaterial and the chiral metamaterial are discussed. In addition, the optical tunability of the metamaterial through nonlinear material excitation and the metamolecule reconfiguration are reviewed in details.

In Chapter 3, the design, fabrication and experiments of the magnetic response tunable metamaterial are presented. The mechanism on the excitation of magnetic response in the metamaterial is investigated. The metamolecule geometric dependence of the magnetic response is discussed. The enhancement of the magnetic response is realized through metamolecule modification. The strength of the magnetic resonance is actively controlled through the micromachined reconfiguration of the metamolecule.

In Chapter 4, the design, fabrication and experiments of two electric response tunable metamaterials are elaborated. The first design realizes a tunability through the change of capacitive coupling between a radiative structure and a non-radiative structure in the metamolecule. This coupling behaves similar as an electromagnetically induced

transparency effect, its theoretical modeling is developed for the theoretical analysis. The second design utilizes the coupling change between two radiative modes in the metamolecule. In addition, the switching of the conductive couplings is demonstrated experimentally that significantly modulates the transmission in the metamaterial.

In Chapter 5, the design, fabrication and experiments of two chiral metamaterials for optical activity manipulation in THz regime are innovated. The first design presents a planar metamaterial with extrinsic chirality. The optical activity is highly dependent on the incident angle of the terahertz wave. The planar metamaterial can be tuned from a chiral structure to an achiral one, which suppresses a giant optical activity to zero. The metamaterial is also switched between the chiral structure and its enantiomer structure, which reverses the polarization rotation direction. The second design presents a semi-3D metamaterial which realizes an intrinsic chirality. Strong optical activity is obtained by collapsing a planar chiral structure into a semi-3D one. The fabrication process of the semi-3D metamaterial is developed and strong polarization rotation is experimentally demonstrated.

Chapter 6 concludes the major contributions of this thesis followed by the recommendations for future works.

CHAPTER 2

LITERATURE SURVEY

This chapter is divided into four parts. The first part of the chapter presents an overview on the metamaterial concepts, fundamental theories, fabrication and applications. The second part of the chapter briefly introduces the optical properties and applications of THz wave and reviews the research development of metamaterial for THz wave control. The third part of the chapter is focused on the study of chiral metamaterials, which is capable to realize significant optical activity and polarization rotation compared with natural materials. The fourth part of the chapter discusses the metamaterial with tunability functionality. The resonant condition and coupling effect in the metamaterial are manipulated in real time through an active control and therefore wide application can be explored. All these works lay the foundation for contributions of this thesis in the research field of THz tunable metamaterials in THz regime.

2.1 Metamaterial Fundamentals

2.1.1 Metamaterial Concepts and Theories

The metamaterial is an artificial material which is designed for control and manipulation of electromagnetic (EM) waves, or sometimes, acoustic waves. The metamaterial consists of large amount of artificially built elements called metamolecules. The metamolecules are usually periodically arranged in space similar with the lattices in natural crystal materials. The structure of the metamolecule is rationally designed to respond to the EM wave in a superior manner that the natural molecules do not, and hence it is named “meta”, implying “beyond” natural materials. The size of each metamolecule is in subwavelength scale. Therefore, the metamaterial can be regarded as a homogenous material. Summarizing the above properties, the explicit definition of the metamaterial is [1]:

“1. Metamaterials are engineered composites that exhibit superior properties not found in nature and not observed in the constituent materials.

2. A metamaterial is an artificial material in which the electromagnetic properties, as represented by the permittivity and permeability, can be controlled. It is made up of periodic arrays of metallic resonant elements. Both the size of the element and the unit cell are small relative to the wavelength.”

Similar with that of natural materials, the optical properties of metamaterial can be interpreted by investigating the integration between the metamolecules and the electric/magnetic field of the EM wave, which is expressed by the Maxwell equations as:

$$\left\{ \begin{array}{l} \nabla \cdot D = \rho_v \\ \nabla \cdot B = 0 \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \times H = \frac{\partial D}{\partial t} + J \end{array} \right. \quad (2.1)$$

where E and H are the electric and magnetic field, D and B are the electric and magnetic flux density while ρ_v and J are the electric charge density and current density. E , H and D , B are related as

$$\left\{ \begin{array}{l} D = \varepsilon E \\ B = \mu H \end{array} \right. \quad (2.2)$$

where ε and μ are the permittivity and permeability of the material. They are the intrinsic properties of the material and usually depends on EM wave frequency, which is called dispersive. The two parameters may be also varied for different wave propagation direction, the value of which are expressed in spatial tensors. ε and μ are usually constrained for natural materials, while for metamaterial, they can be flexibly designed by properly constructing the metamolecule structures.

2.1.2 Metamaterial Optical Properties

Optical properties of the metamaterial have been discussed which are rarely found in natural materials. These properties are obtained through different metamolecules designs based on profound physical principles. In this section, the optical properties and basic principles are reviewed.

Table 2.1 Material categorized by permittivity and permeability

Permittivity	Permeability	Materials
+	+	isotropic dielectrics
-	+	metals at below plasma frequency
+	-	ferrites at sub-microwave frequencies
-	-	Left-handed material at flexible frequency

2.1.2.1 Left-handed relation in metamaterial

The metamaterial has attracted many research attentions because of its ability to realize a medium with flexible permittivity ϵ and permeability μ . A most exciting medium realizable through the metamaterial possesses both negative ϵ and negative μ . The double negative parameter medium, which exhibits a negative refractive index, is not found in nature and could derive an unprecedented control on EM waves.

The double negative medium was studied by the Russian Physicist Victor Veselago in as early as 1967 [16]. From Maxwell's equations, Veselago deduced that

$$\begin{cases} \mathbf{k} \times \mathbf{H} = \omega \epsilon \mathbf{E} \\ \mathbf{k} \times \mathbf{E} = -\omega \mu \mathbf{H} \end{cases} \quad (2.3)$$

where k is the wave vector and ω is the angular frequency of the wave. From Equation 2.3, E , H and k have right handed relation if ϵ and μ are both positive, which is the case in natural materials. In a double negative medium, instead, the E , H and k have a left handed relation. The pointing vector $E \times H$ points to the energy flow direction and the wave vector k points to the phase velocity direction. Therefore, the energy flow and phase velocity is in same direction in natural materials while opposite direction in left handed metamaterials. The sign of the permittivity and permeability of the materials are compared in Table 2.1 and examples of the corresponding material types are listed.

Negative permittivity can be commonly found in metals at frequency below their plasma frequencies, which are usually in infrared or optical regime. Negative permeability, on the other hand, occurs in some ferromagnetic materials at microwave frequency range. The double negative medium, however, has not been found in nature [13]. Therefore, Veselago's theory did not attract much research attention until 1999 when Sir John Pendry proposed a metamaterial which makes the double negative medium become possible [17]. The metamolecule is called metallic split-ring resonator (SRR). It realize a strong magnetic response, and therefore negative permeability at the resonant frequency which largely depends on the metamolecule's scale. Later in 2001 the negative refractive indexed metamaterial is experimentally demonstrated at microwave frequency regime. The metamolecule of the material consists of a SRR and a metallic strip, which induces negative permeability and negative permittivity in the same frequency band [18]. The negative parameters are retrieved later through a retrieval method using the S-parameter of the metamaterial [19, 20]. Many successive designs like slab pair [21-24] and fishnet structures [25-31] are proposed to obtain the negative refractive index at different frequencies. Consequently, the left handed metamaterial are realized across the EM wave band from microwave [18, 32-34], THz wave [35-37], infrared light [38, 39] to visible light regime [40-43]. In addition, the negative refractive index metamaterial in wide band or multi-band [40, 44-48] are also realized.

2.1.2.2 Electromagnetically induced transparency (EIT)-like effect in metamaterials

Electromagnetically induced transparency (EIT) is a destructive interference of quantum probability amplitudes between two quantum states. One state directly absorbs

the incident light energy and the other one does not [49, 50], which are named as the excited state and the metastable state, respectively. The two states are destructively interfere with each other through an optical pumping. This interference significantly suppresses the light absorption over a very narrow spectral band and exhibit an enhanced transmission. Meanwhile, an extremely high dispersion is realized due to the interference, which can substantially slow down the group velocity of the light [50].

The quantum EIT effect is usually difficult to be observed due to the critical excitation requirements, which, on the other hand, can be mimicked with a classical coupled oscillator system [51, 52]. The destructive interference induce extraordinary transmission is demonstrated in classical optical systems like microcavities [53, 54], photonic crystals [55-58] and optical resonators, which is called EIT-like effect and has great potential to realize a slow light. However, the above structures are usually much larger than the wavelength of the EM wave. Metamaterial, which controls light in subwavelength dimension, is demonstrated as a promising alternative to obtain the EIT-like effect [59-72]. The destructive interference in metamaterial can be induced through two kinds of mechanisms, i.e. the “trapped mode” realized by asymmetric coupling [59-65] and the resonance from coupling between radiative mode and non-radiative mode [66-72]. A narrow band with extraordinary transmission and high dispersion are successfully demonstrated across the EM spectrum from microwave [59, 71], THz [70, 72] to infrared [66, 68] and visible optical range [73]. Benefiting by these novel properties, the EIT metamaterial has large potentials on slow light [74, 75] and sensing [76, 77] applications.

2.1.2.3 Chirality in Metamaterials

Chirality describes a structure that does not superimpose with its mirror image, or, its enantiomer [78]. It usually occurs in biomolecules and results from the presence of the asymmetric bond of carbon atom. Although the two enantiomers have same chemical properties due to the same atom constitution and chemical bond, their pharmacological effect is quite different and therefore it is very important on the chiral study of the molecules. On the other hand, the physical properties of optical activity, including circular birefringence and circular dichroism, are also induced in the chiral structures [79]. Therefore, chirality offers good opportunities for the metamaterial to control the EM wave [80-82], which is viewed in details in Section 2.3.

2.1.2.4 Other Properties in Metamaterials

Many more novel properties are also developed according to different principles. A ϵ -near-zero (ENZ) metamaterial is studied which a permittivity close to zero [83-85]. The ENZ metamaterial squeezes most energy of an electromagnetic wave into an ultra-narrow channel due to effective “infinite” phase velocity in the metamaterial.

Recently, the planar metamaterials, i.e., the metasurfaces, is another breakthrough due to its extraordinary control of light using simple planar textures [86]. The phase delay of the transmitted/reflected wave can be arbitrarily modulated spatially and the wavefront can be effectively controlled. Various metasurface designs are proposed for different optical functions and devices like beam steering [86-90], aberration free lens [91-94], waveplates [95-98]. The metasurface, for its wide

application, has been intensively studied across the EM wave spectrum from microwave [95], THz [99], infrared [91, 100, 101] to optical visible light [92, 102].

2.1.3 Metamaterial Fabrication Methods

The fabrication technique for metamaterials are developed according to the scale, structure of metamolecules and the architecture of the metamaterial. For metamaterials operating in the microwave regime, the metamolecule size is in millimeter. Such metamaterial can be fabricated through relative simple processes such as the print circuit board (PCB) printing method, which is not surveyed here. This section mainly focuses on the fabrication techniques for the metamaterial with metamolecule size in micrometer and nanometer scale. These fabrication methods includes “top-down” mechanisms like lithography and “bottom-up” techniques called self-assembly methods [12]. Here the “top-down” methods are reviewed as follows.

2.1.3.1 Optical lithography

The micrometer sized metamolecule of planar metamaterials is usually fabricated using optical lithography technique. The optical lithography is a maturely developed technology which is compatible with CMOS fabrication process. In this technique, a photoresist layer is deposited on the structure and exposed to the light (mostly the UV light) under a mask. The pattern on the mask is then transferred to the photoresist and the exposed parts are removed. The structure layer is then etched and metamolecule pattern is left. In another lift off processes, the structure layer is deposited after the photoresist develop. The structure layer deposited on the exposed part will remain on the

substrate and the part on the photoresist will be removed. The optical lithography has the advantage to realize a massive and low cost production. However, its resolution is largely limited by the optical diffraction limitation and is about hundreds of nanometers under commonly used UV light with wavelength of either 284 nm or 193 nm.

2.1.3.2 Electron-beam lithography

For planar metamaterials with nanometer sized metamolecules, electron-beam lithography is commonly used. Electron-beam lithography differs from optical lithography that the electron beam is used to draw the pattern on the resist which is electron sensitive. The structure layer is then etched or lift off as that in optical lithography process. The electron-beam lithography realizes much smaller line widths on the order of 10 nm. However, it has the limitation of high cost and low throughput and thus not recommended for massive fabrication applications.

2.1.3.3 Nanoimprint lithography

The nanoimprint lithography (NIL) is a novel method to transfer a predefined structure from a template (mold or stamp) to the resist (thermoplastic polymer) on the substrate. The resolution of this method depends on the line width on the mold and the material of the mold. NIL is capable to realize sub-10 nm features over large area by repeating the structure transfer using the mold. Therefore, it has advantages of high throughput, low cost and high resolution. However, it also has the disadvantage like the mold sticking, uniformity problem of the printed surface and the swelling of the mold.

2.1.3.4 Multilayered Metamaterial Fabrication

For multilayered metamaterial fabrication, it basically also uses the above lithography techniques. Multiple layers could be deposited successfully in the lithographically defined window when the shape of the layers are the same. Otherwise, for different layer shapes, new lithography is need and importantly, alignment between the layers are required. The alignment resolution depends upon the EBL system, which is usually about 30 nm.

2.1.4 Metamaterial Applications

Since the metamaterial exhibit much more flexibility on the control on the EM wave, tremendous applications have been proposed by designing different types of metamaterials, which are reviewed in this section.

2.1.4.1 Super-resolution imaging

The optical imaging is always critical for ultra-small sized observation and is widely used in the areas such as biological detection and integrated circuit fabrication [103, 104]. The resolution of the imaging obtained through traditional microscopy is always limited to about half wavelength of the light [105]. This is known as diffraction limitation and is an intrinsic problem for far field diffraction, or Fraunhofer diffraction. The diffraction limitation occurs due to the information loss, or the decay of the high spatial-frequency evanescent wave, when the light is propagating through a far field distance. A near-field scan are alternatively used, which measures the imaging

information in near field distance, usually within one wavelength range [106]. However, this method is limited in short distance measurement and causes sample damaging.

A perfect lens based on negative refractive index metamaterial is proposed for subwavelength resolution imaging [9]. In this work, the focus of all Fourier components of the imaging is theoretically demonstrated. Later a superlens are designed which enhances the evanescent wave of the image [8, 107-110]. A resolution of one-sixth of the illumination wavelength is then realized using a silver slab layer [8]. This superlens, however, still confines the imaging measurement in a near field range, and a far-field measurement is highly desired. One solution is to modify the silver slab into periodic corrugations which convert the evanescent waves to propagating waves [111]. Similar approaches like using subwavelength gratings [112, 113], metallic rods [114, 115] or nanowires [116] are also proposed. In the meantime, a hyperlens, consisting an anisotropic media with the spatial permittivity tension in hyperbolic relation, is proposed to convert the evanescent wave to propagating one [117, 118]. The hyperlens is usually made of multiple metal-dielectric layers and the super-resolution in far-field is demonstrated [119-125]. In spite of the successful demonstration, the hyperlens, on the other hand, is not capable to focus the plane wave, or, in other words, not able to do the Fourier transform. A metalens is instead designed which combines a phase compensation coupler with the metamaterial to support high wave vectors [126-128]. Besides the mechanism of the evanescent recovery for super-resolution, a super-oscillatory lens is alternatively proposed. A binary mask is designed to oscillate the band-limited function faster than the highest order Fourier components and realizes the super-resolution [129-132].

2.1.4.2. Perfect Absorption

The EM wave usually undergoes large losses when interacting with the metamaterial due to the Ohmic dissipation and scattering by the metamolecules. However, the loss could also be utilized to realize a perfect absorber. The mechanism of the perfect absorber is to minimize the transmitted and reflected wave simultaneously. It is usually difficult to suppress the reflection to zero for natural materials due to the impedance mismatch with free space. The impedance of metamaterials, instead, can be easily designed to match perfectly to the free space by manipulating the permittivity and permeability. On the other hand, the transmission could be minimized through strong electric and magnetic resonance. As a result, a perfect metamaterial absorber is realized [133-135]. As demonstrated in [134], a metamaterial absorber obtains an absorption coefficient as high as 2000 cm^{-1} in THz range. Later, a similar approach is proposed which blocks the transmission simply by utilizing a metal layer on the backside of the metamaterial. Therefore, no transmission is allowed below the optical frequency and the absorption can be maximized as long as the impedance matches to the free space [136-140]. To explore its application in different fields, the metamaterial absorbers are optimized in different aspects such as polarization independence [135, 141], wide incident angle [136, 142], broad band [137, 143] and multi-band absorption [139, 144-146]. The perfect absorption have been successfully demonstrated from microwave [147, 148], THz wave [134, 149], infrared light [138, 150, 151] to optical visible light regime [137].

2.1.4.3 Sensing

As well understood, the property of metamaterials relies on its geometric shape, and therefore, the optical response measurement on metamaterials is a promising approach to detect the structural change. The structural change is caused by either external strain force [152-154] or the expansion stress from thermal excitations [155], which can be monitored dynamically. Accordingly, metamaterial sensors for telemetry [152, 153] which advances in the wireless measurement compared to the traditional foil strain gauge. In addition, bio-compatible metamaterial sensors [154] are also designed.

The metamaterial is also capable to confine electrical field in localized areas, such as in the gaps between the SRRs. The confinement largely depends on the metamaterial's effective refractive index, which varies significantly with different substance on the metamaterial. Metamaterials can be tuned dynamically to optimize the energy confinement and achieve high sensitivity on the refractive index fluctuation. Such metamaterials have been reported for environmental detection and bio-sensing which are of label-free and low cost [156-158].

2.1.4.4 Others

Many more applications are also explored based on the unique property of metamaterials. The invisible cloak, which protect the object from being detected, is one of the most fantastic applications on light control. The metamaterial, right after its realization, is proposed for the cloaking by distorting the light path round the object to be cloaked by realizing some extreme permittivity and permeability values [7, 159-161]. Another approach for concealing the object is to use metamaterial based optics

transformation which uses the coordinate transformation and conformal mapping to recreate the pattern of the objects [162-165]. The metamaterial is also widely applied for antenna design which flexibly controls the directivity, beamwidth and gain because of its arbitrary designed permittivity and permeability [166-171]. Such antenna also advances in its compact scale due to the subwavelength manipulation [172, 173]. The polarizer and waveplate are also demonstrated in different frequency band using metamaterials with strong chirality [174, 175] or anisotropy [176-179], which manipulates the polarization states of the incident wave. Recently, metamaterial based holograms are constructed and provide another approach for the light control and communication [180-183].

2.2 THz Metamaterials

2.2.1 THz and THz Applications

The THz wave is the EM wave with frequency ranging from 0.1 THz to 10 THz, or the wavelength from 3 mm to 30 μm , correspondingly [184]. In the EM wave spectrum, THz wave is sandwiched between microwave and far IR wave. The microwave and IR have been intensively studied for a long time, however, the THz remains a spectrum which is not maturely researched and utilized. This is because the generation source and the measurement instrument for THz is not that available compared to that for microwave and IR wave which uses well developed electronic and photonic technologies. In recent decades, advanced technologies are proposed for the THz generation and detection, including the ultrafast laser based optical rectification process, optical parametric process, semiconductor laser based inter-subband transition and electronic device based frequency multiplication [185, 186].

The THz radiation attracts high research interests not only because it is an undeveloped spectrum, but also due to its specific optical characteristics. The THz wave can penetrate through many dielectric material and no-polar liquids with a low loss, making it a potential substitution to X-ray and ultrasonic for imaging applications. It also can be used in non-contact detection for drugs or weapons, etc. The THz wave also has the advantage of low photo energy, which does not damage the biological sample. In addition, the rotation and vibration frequency of many biological molecule locates in the THz regime, so the THz wave is used as a sensitive detection method for disease therapy and organisms function monitoring. Furthermore, compared with microwave and radio

frequency, THz wave has much wider bandwidth and can be applied for short-range communications [187].

2.2.2 THz Metamaterials

THz technology is fast developed and devices and materials for controlling and manipulating the THz wave are also in large demand. Common electronic devices, however, can not modulate the THz signal effectively due to the high frequency of the THz wave. On the other hand, the natural material usually responds to the THz wave weakly through the form of molecular rotation or vibration. The metamaterial, instead, is an important approach for the THz wave control because it is able to induce strong resonance of the EM wave at desired wavelength by simply choosing a proper metamolecule size.

Strong response to the THz wave is successfully obtained in metamaterials. A magnetic response is demonstrated at around 1 THz through a planar metamaterial under oblique incidence [188]. The time-varying magnetic field of the THz wave passes through the metamaterial surface plane and induces the free electron oscillation. To obtain strong magnetic THz resonance at normal incidence, a stand-up metamaterial is proposed which constructed a 3D metamaterial [189]. In addition, a dual band magnetic response is realized at both 4.4 THz and 8.6 THz by a hybrid metamaterial [190], which paves a way to wideband control. On the other hand, metamaterials for electric response to THz wave are also demonstrated and negative permittivity [191], high dispersion[192] and dual band resonance [193] are achieved. Furthermore, negative refractive indexed metamaterials are realized by inducing negative permittivity and negative permeability

simultaneously at same THz frequency band [35]. THz metamaterials with other properties such as low loss [194, 195] and extraordinary transparency [196-198] are also proposed for different applications.

The THz metamaterial is used to control the wave polarization state [11, 199-201], phase delay [202, 203] and wave front[204], etc. Based on the promising modulation function ability, wide applications through the THz metamaterial are proposed such as perfect absorbers [134, 139, 205], polarization rotators [206, 207], beam steering [99] and imaging [208, 209].

2.3 Chiral Metamaterials

A chiral structure is the one which does not superimpose with its mirror image. The structure and its imaging structure are called a pair of enantiomers. The chirality is quite common in many biomolecules with asymmetric carbon atoms. The word "chiral" is derived from the Greek word for hand, because the right and left hand (the 3-D structure) do not superimpose with each other and is a good example to illustrate the chirality [78].

2.3.1 Chirality and Optical Activity

The history of optical activity can be traced as early as 1811, which is found by the French physicist Dominique Arago. He observed that a beam of linearly polarized light has a polarization rotation when it passing through the optic axis of a quartz material. The ability of material to rotate the polarization direction is named optical activity. Other material like sugar, tartaric acid and turpentine are later found to also have the optical activity. In terms of polarization rotation direction, the optical activity can rotate the electric field direction of the incident wave in clockwise or counter clockwise, which are noted as dextrorotatory, or d-rotatory and levorotatory, or l-rotatory, respectively. The two rotatory ways are later found to be essentially related to the structure of the molecule, which does not superimpose with its mirror imaging.

Later in 1825 Fresnel addressed that the optical activity can interpreted by regarding the linear polarization EM wave to the superposition of in phased right circularly polarized and left circularly polarized light with same amplitude. The electric

fields of the right circularly polarized light and left circularly polarized light are expressed as [210]

$$\begin{cases} E_R = \frac{E_0}{2} [\hat{i} \cos(k_R z - \omega t) + j \sin(k_R z - \omega t)] \\ E_L = \frac{E_0}{2} [\hat{i} \cos(k_L z - \omega t) - j \sin(k_L z - \omega t)] \end{cases} \quad (2.4)$$

where k_R and k_L is the wave vector of the two polarized light. The superposition of the two light is linearly polarized when $z = 0$ can be expressed as

$$E = E_0 \hat{i} \cos \omega t \quad (2.5)$$

While after propagating in the medium with a distance z_0 , the resulted electric field is

$$E = E_0 \cos \left[(k_R + k_L) z_0 / 2 - \omega t \right] \left[\hat{i} \cos (k_R - k_L) z_0 / 2 + j \sin (k_R - k_L) z_0 / 2 \right] \quad (2.6)$$

There is an angle rotation due to the phase difference of the two oppositely circularly polarized light after propagating through the material, noted as θ , which is given by

$$\theta = -(k_R - k_L) z_0 / 2 \quad (2.7)$$

As the wavenumber related with the wavelength in free space can be expressed as

$$k = \frac{2\pi n}{\lambda_0} \quad (2.8)$$

θ can be expressed in terms of the refractive index for the right circularly polarized light n_R , and the refractive index for the left circularly polarized light n_L as

$$\theta = \frac{\pi d}{\lambda_0} (n_L - n_R) \quad (2.9)$$

In fact, these equation skipped the absorption issue by the material and only the real part of the refractive index is considered. As a result, the transmitted wave is still

linearly polarized with a rotation angle θ . This rotation caused by the real part of the refractive index, is known as circular birefringence.

However, absorption always exists when an EM wave passing through the material and the absorptivity of the chiral material can be different for the right circular polarized and left polarized light. The difference of the absorptivity, is called circular dichroism. As a result, the corresponding transmitted amplitudes, A_R and A_L , do not equal. The transmitted wave is therefore no longer a linearly polarized wave. Instead, it is an elliptically polarized light. The ellipticity χ of the light can be expressed as [211]

$$\chi = \arctan \frac{A_R - A_L}{A_R + A_L} \quad (2.10)$$

The imaginary part of the refractive index is responsible for the absorptivity, which is noted as n_R'' and n_L'' , and the ellipticity can be expressed using the refractive index value as

$$\begin{aligned} \tan \chi &= \left[\exp\left(-\frac{2\pi n_R'' l}{\lambda}\right) - \exp\left(-\frac{2\pi n_L'' l}{\lambda}\right) \right] / \left[\exp\left(-\frac{2\pi n_R'' l}{\lambda}\right) + \exp\left(-\frac{2\pi n_L'' l}{\lambda}\right) \right] \\ &= \tanh \left[\frac{\pi l}{\lambda} (n_R'' - n_L'') \right] \end{aligned} \quad (2.11)$$

which can be simplified to

$$\chi = \frac{\pi l}{\lambda} (n_R'' - n_L'') \quad (2.12)$$

when χ is small, and it becomes proportional with $(n_R'' - n_L'')$.

The difference of the refractive index, both real part and imaginary part, for the two circularly polarized light, originates from the different interaction with the chiral

materials. The couplings between the electrical field and the magnetic field of different circular polarized light in the chiral structure are opposite. Together with other electric or magnetic field related interactions, the refractive indexes are different for right circularly polarized and left circularly polarized EM wave. The electromagnetic coupling factor, k , together with permittivity and permeability of the material, can be used to express the relation among electrical flux, magnetic flux and electric field and the magnetic field in the material as

$$\begin{pmatrix} D \\ B \end{pmatrix} = \begin{pmatrix} \epsilon_0 \epsilon_r & -i\kappa / c \\ i\kappa / c & \mu_0 \mu_r \end{pmatrix} \begin{pmatrix} E \\ H \end{pmatrix} \quad (2.13)$$

and finally derived that

$$n_{\pm} = \sqrt{\epsilon_r \mu_r} \pm \kappa = n_0 \pm \kappa \quad (2.14)$$

Therefore, a material with non-zero k has different refractive indices for the two circular polarized light. The optical activity is then induced with both the circular birefringence and the circular dichroism.

2.3.2 Chiral Metamaterials

The chiral metamaterial is a metamaterial consisting of chiral structured metamolecules. It attracts wide research attention due to many novel optical functions, one of which is the realization of negative refractive index [212]. The negative refractive index, as discussed in Section 2.1.2, is initially achieved in a material with both the negative permittivity and permeability. The medium with the negative permittivity and permeability in microwave regime is widely demonstrated with metamolecules in

millimeter size. However, that is quite difficult to be implemented in optical regime which covers wavelength from 400 nm to 780 nm due to the saturation of the magnetic response at optical frequencies in the metamolecules as small as tens of nanometers [213]. On the other hand, the chiral metamaterial is proposed to obtain the negative refractive index from a strong electromagnetic coupling between the chiral metamolecule and the EM wave instead of the negative permittivity and permeability. Based on Eq. 2.14, a chiral metamaterial can possess the negative refractive index at one circular polarization state when the absolute value of k is strong enough. A chiral metamolecule model of a wounded helix coil is theoretically studied for the negative refractive index [212, 214]. Many indefinite chiral metamaterials with both isotropic and anisotropic parameters are studied and the backward propagation is investigated [215-218]. The enhancement of evanescent wave and subwavelength focusing is also predicted in a bi-isotropic chiral media [219]. Different chiral structured metamaterials are successively proposed and the negative refractive index is both analytically and numerically confirmed [220-223]. The experimental demonstration on negative refractive index by the chiral metamaterial is later demonstrated in a 3D chiral structure [224]. In this work a negative refractive index of ~ 5 is realized in the THz regime at left circularly polarized incidence. In contrast, the refractive index is positive for right circularly polarization, which is consistent with the theoretical analysis. Later the negative indexed medium is also demonstrated in microwave with a standing up 3D structure [225] and in radio spectrum with a Swiss roll [226]. In spite of the successful demonstration in the relative low frequency regime, the negative medium is usually hard to be obtained in optical range through the 3D chiral structure due to difficult fabrication. Multi-layered planar chiral metamaterial is then

proposed which significantly simplifies the fabrication processes and negative refractive index is observed experimentally [227-231].

Apart from the negative refractive index, the chiral metamaterial is also able to realize much stronger optical activity compared to that from natural materials due to giant electromagnetic coupling in the metamolecule. A pioneer work observes a polarization rotation up to 30° in the diffracted light from a planar chiral metamaterial [232]. Later an optical activity is obtained from a non-diffracted planar chiral metamaterial [233, 234]. This optical activity is based on the symmetric breaking effect due to the substrate. Later a stronger optical activity is realized through a 3D metal screw hole arrays [235]. Some other 3D chiral metamaterial structures are also reported with giant optical activity [236-238]. However, the 3D structure is difficult to be fabricated, especially for the optical wave range. A two layered planar structure, which are more easily fabricated, are possessing strong optical activity [239-241]. The optical activity is also realized in achiral metamaterials with oblique incidence, which is due to the asymmetric architecture formed by the metamaterial and the wave vector of the incident wave [242-245] and such chirality is referred as extrinsic chirality. Through the optimized chiral metamaterial, giant optical activity are successfully demonstrated in microwave [231, 246], THz [10, 11], infrared and optical visible range [247-249]. In addition, the nonlinearity of the optical activity in chiral metamaterials is also studied [250].

Nonreciprocal transmission, like the asymmetric flowing electric current through an electric diode in opposite directions with same electric bias, is essential for signal processing. Alike the asymmetric electric current, an asymmetric optical

transmission is demonstrated in planar chiral metamaterials without breaking the reciprocity. The asymmetric transmission is based on the different cross-polarized transmission in the forward and backward propagation, which is early demonstrated for circularly polarized wave using a planar chiral metamaterial [251-253]. Bi-layered chiral metamaterials is also studied for enhancing the asymmetric transmission [254, 255]. Later the asymmetric transmission is also demonstrated in linearly polarized wave in multi-layered chiral metamaterials [256-259]. In addition, the asymmetric transmission at multi-band is also investigated [260, 261].

In conclusions, the chiral metamaterial advances in the capability to realize negative refractive index, giant optical activity and asymmetric transmission. It has high potential application in the fields of optical imaging, detection and signal processing.

2.4 Tunable Metamaterials

The artificial nature of the metamaterial not only provides the ability to explore various optical properties through different metamolecule designs, but also leaves much flexibility to control the properties in real time through external excitations [14, 262]. Tremendous tunable approaches are proposed, which can be mainly categorized into two groups: one uses the nonlinear behavior of the consisting materials, the other one reconfigures the structure of the metamolecules or the lattice arrangement. The tunability not only offers a good opportunity to study the physical significance in different metamaterial tuned states, but also explores wide applications in the function of dynamic control.

2.4.1 Nonlinear Tunable Metamaterials

Nonlinearity in optics usually refers to a nonlinear response of electric polarization to the electric field of the incident wave. Here, we refer the “nonlinearity” to a more general way that the optical properties of a material are changed under an external excitation including EM wave pumping, thermal effect, electric field and magnetic field, etc. Therefore, the effective parameters of the metamaterial consisting of such nonlinear materials are also tuned under the excitations. In the following sections the metamaterial tuning is reviewed based on four types of nonlinear materials, i.e. ferrite material, superconductor, liquid crystal and semiconductor.

2.4.1.1 Ferrite material based metamaterials

Ferrite materials, such as the yttrium iron garnet (YIG), respond to the external magnetic field and its permeability is tuned depending on the field intensity. The tunability can be used to control the effective permeability of metamaterials. YIG slabs are firstly deposited on the substrate of metamaterial, which performs a resonant peak shift [263] and bandwidth tuning [264] through the external magnetic field control. The left-handed property of ferrite metamaterial is demonstrated as well [265] and the negative permeability is controlled by a magnetic field to the YIG. It is also possible to embed a metallic structure inside the ferrite materials [266, 267], which makes the ferrite metamaterials isotropic to the static magnetic field. Furthermore, ferrite material can be fabricated as the metamaterial consisting element to achieve a better control of the permittivity [268, 269].

It is also interesting to recall the Faraday Effect, which rotates the incident wave polarization according to the external magnetic field. The Faraday rotation has been realized widely by using ferrites [270-272]. Together with the ferrites-built metamaterials, the control of external magnetic field is highly attractive to build a tunable polarization rotator and optical isolator.

2.4.1.2 Superconductor based metamaterial

The tunability of ferrite based metamaterials is well demonstrated. However, the corresponding working spectrum is limited in microwave regime because the magnetic permeability of ferrite tends to be a constant of one as the frequency goes up to optical regime. Superconductor, instead, is capable to response to EM wave at high frequency

regime. It attracts many interests in tunable metamaterial design, and the conductivity is effectively tuned by temperature control. The resistivity of superconductor drops nearly to zero when the temperature is decreased below its critical temperature T_c . Therefore, the superconductor based metamaterial has large tunability on the resonant frequency and quality factor (Q factor), which is defined as the ratio of the center frequency over the half-power bandwidth frequency. The mostly common superconductor for tunable metamaterials are niobium (Nb) and niobium nitride (NbN), which have critical temperature at 8.65K and 15.78 K, respectively [195, 273, 274]. Nb is firstly used in the metamaterial design and the insertion loss is well controlled. The negative refractive index is realized in the superconducting state, which can be switched to positive when temperature rises up to 10 K [273]. NbN, with a higher T_c , is also reported to shift the resonant frequency of metamaterials by temperature tuning [195, 274]. However, the T_c for Nb and NbN is extremely low which makes the tuning condition hard to be realized.

Another superconducting material, yttrium barium copper oxide (YBCO), has a T_c around 90K [275], which is higher than the boiling point of liquid nitrogen (77K). This makes it an excellent alternative for the superconducting tuning in metamaterials [276-278]. In addition to temperature tuning, superconductor resistivity can be controlled by external magnetic field as well. The magnetic field affects the magnetic penetration depth and critical current density of the superconductor [279] which drives the superconductor from the superconducting state to the normal state [194, 280, 281] and changes both the transmission intensity and the Q factor of the incident wave.

The tunable conductivity of the superconductor is used for the EM wave transmission tuning, among which electromagnetically induced transparency receives

much attention, which is previously discussed in Section 2.1.2. The tuning of EIT effect is realized in superconductor-based metamaterials through temperature control [67, 70, 71, 282], where superconductor and normal metal material are used to construct different energy states. The metamolecule consists of two SRRs made of superconductor Nb with a copper wire in between. The SRRs are superconducting when the temperature is below T_c and has different energy state with the copper wire. Significant EIT effect is induced, which is then totally suppressed when the temperature rises above T_c . [282].

2.4.1.3 Liquid crystal based metamaterial

The superconducting tuning is largely restrained by the low temperature requirement. Although experimental demonstrations can be easily realized in laboratory, for real applications, controlled methods with room temperature compatibility are preferred. Liquid crystal experiences a phase transition when temperature rises above the phase transition temperature T_p [283], which is usually much higher than the critical temperature of superconductor, for example, the 5CB liquid crystal has a T_p of 35 °C [284]. The phase transition is easy to realize and thus attracts wide research interests for tunable metamaterial research [284-290]. Nematic liquid crystal is commonly used for the tunable metamaterials. Its permittivity in two orthogonal polarizations is 2 and 4, respectively, which thus realizes a refractive index tunability of about 0.6 when temperature increases above T_p [291]. As reported in [284], the metamaterial consists of metallic nanorods covered by the nematic liquid crystal. With a change of refractive index of liquid crystal by Δn of 0.15, the reflection peak of metamaterials shifts from 650 nm to 632 nm.

The phase transition of liquid crystal is not constrained by thermal excitation. The uses of electrical [292-294] or magnetic bias [295, 296] to tune liquid crystal metamaterial are also studied, which have wide applications such as imaging process. The transmission is well tailored by both electrical bias and input power control. However, the response time for these methods are usually in the order of millisecond [297, 298]. As reported later, the laser pulse excited liquid crystal is an excellent candidate to further improve the response time [299]. By controlling the laser pulse energy, the output of metamaterial can be switched off in 25 ns, which not only provides a faster tuning speed, but also offers much opportunity in the all optical switching area.

2.4.1.4 Semiconductor based metamaterial

Ferrite material, superconductor and liquid crystal based metamaterials usually hindered by the problems of high cost or extreme operating conditions, which prevent massive fabrication of the tunable metamaterials. Semiconductor based metamaterials, instead, are compatible with the CMOS processes and has great advantages in the fabrication. The nonlinearity of most semiconductors relies on the free carrier concentrations, which depend on the semiconductor band gap, carrier density and potential barriers at the junction of two materials, etc. For semiconductor based tunable metamaterial, the nonlinear effect of metamaterial consisting with diode is theoretically discussed [300] and experimentally demonstrated [301]. Later, a varactor diode based tunable metamaterial is demonstrated to shift the reflection dip in the microwave regime by both electrical voltage bias and input power control [302]. This approach is further improved by combining an inductive coil with the varactor diode, which changes the sign

of nonlinearity of the metamaterial [303]. The varactor diode inserted split ring is built periodically later to realize tunable metamaterials [304, 305]. The tunability by input power control is demonstrated and the nonlinearity of harmonic generation is observed. In addition, a photodiode is used to supply the voltage bias for the varactor diode, which realizes the optical control of the tunable metamaterial [306]. The diode based tunability is usually resulted from but not limited to capacitance change. For example, the resistivity of pin diode can be tuned by electrical voltage bias [307]. The tuning not only shifts the resonant frequency of the metamaterial, but also controls the Q factor of the resonance.

The direct diode insertion for the tunable metamaterial is normally constrained in microwave spectrum because of the difficulty in scaling down with an inserted diode. For higher frequency operating, Schottky diode based tunable metamaterial is proposed, which is constructed by depositing metallic pattern on the n-doped gallium arsenide (GaAs) layer [202, 308-310]. For example, a reverse biased electrical voltage is applied on the structure. The potential barriers between metal and GaAs are increased and the movement of the free carriers in between is controlled [308]. Compared to the varactor diode insertion, the Schottky diode based metamaterial is easier to be scaled down to realize the operation in THz or optical spectrum regime. In addition, the switching speed of Schottky diode is much faster than that of the varactor diode, which can go up to picosecond.

The conductivity of semiconductor can also be tailored for tunable metamaterial, which largely depends on the free carrier density. With sufficient absorbed energy, the electrons in the valence band of the semiconductor are excited to the conducting band

and become free carriers, which can be realized through an optical excitation. This approach is demonstrated through optical pumping of an amorphous Si layer in a fishnet structured metamaterial [311, 312]. The increased conductivity of Si tunes the transmittance of the metamaterial. Later, instead of the whole Si layer, the photoconductive Si is grown at the gap of the metallic pattern, which demonstrates both red and blue shift of metamaterial resonance [48, 313, 314]. When IR pumping increases to $294.6 \mu\text{J}/\text{cm}^2$, the carriers cross the silicon band gap and the metamaterial transmission dip experiences a blue shift from 0.76 THz to 0.96 THz, which corresponds to the tuning of the conductivity of photoconductive Si from 1 to $1.0 \times 10^5 \text{ S/m}$. The ability to achieve both red shift and blue shift provides much opportunity for the optical controlled metamaterial to be utilized in all optical devices.

Semiconductor based tunable metamaterial is not constrained in GaAs or Si. Other semiconductors are also reported such as InSb [315, 316] or VO_2 [317-319]. InSb has a band gap of 0.17 eV, which is much smaller than that of GaAs and Si. Therefore, lower energy is needed for the excitation of the free carriers, which makes temperature excitation possible. VO_2 transits from an insulating phase to a metallic phase when it is heated above the transition temperature of 68°C . This phase transition completes in sub-picosecond [320] and approximately 100 nm shift in near-IR range is reported in [317].

2.4.2 Reconfigurable Tunable Metamaterials

The reconfigurable metamaterials are defined as the metamaterials either the shape of which can be distorted in macroscopic view, or the metamolecules of which can be reshaped or moved in microscopic view. As the optical properties are largely

dependent on metamolecule structure and inter-coupling, it can be effectively tuned through the reconfiguration. Two approaches are reviewed for the reconfigurable tunable metamaterial in this section. One is the flexible substrate metamaterial which is deposited on a soft substrate. The other is the micromachined tunable metamaterial, in which the structure of the metamolecules are changed driven by micromachined actuators.

2.4.2.1 Flexible substrate metamaterial

In most cases, the metamolecules are deposited on a rigid substrate to ensure an ordered arrangement of the metamolecules. Conventional dielectric materials are usually used as the substrated such as the silicon, FR4 or glass. Therefore, the metamaterial's contour is fixed as a slice or a bulk. However, for some particular applications such as absorption, sensing, cloaking and wearable electronics, a metamaterial with a flexible shape is highly desired. Fortunately, the artificial nature of metamaterial not only allows different metamolecule structures, but also offers much flexibility to select alternative substrates. Different with conventional metamaterials, flexible substrate metamaterials are developed on relatively soft and elastic materials such as polyimide [321], polydimethylsiloxane (PDMS) [322], or even silk [323] and paper [324]. These substrates can be stretched, bent or even rolled up, which are capable to tune metamaterial responses in different spectra from GHz to visible regime [325, 326]. For example, a PDMS based metamaterial manifests high frequency tunability under external strains. As being stretched, the gap inside the metamolecule expands and the electromagnetic response performs a red shift in IR regime. Reversibility after the

expansion should also be considered, which improves the recyclability of the metamaterial [322].

In addition to flexible substrate, another novel approach to deform the metamaterial is demonstrated by building a substrate-free structure which is only consisted of metal pattern. All metamolecules are connected as a whole and sufficient large strength is needed for structure free-standing and deforming. A meta-foil constructed of periodic connected S-string metamolecule is reported to realize high flexibility [327, 328]. Transmission can be significantly reduced as the incident angle increases by bending the structure instead of moving the source.

Besides significant tunability, the flexible metamaterial has great advantages on constructing a multi-layered metamaterial. Compared to the method of growing multi-layers on the substrate to fabricate the 3-dimensional metamaterial, the stacking of flexible layers has high advantages in low cost and massive fabrication. The stacking layer responds in the THz [329-332] and near-IR regime [333, 334], which can go up to optical spectrum as well [335].

2.4.2.2 Micromachined tunable metamaterial

Metamaterials is a material largely depending on the molecule shape. Therefore, reshaping the metamolecule by external forces is a promising approach to realize a tunable metamaterial. However, reconfiguring individual metamolecules, especially for those with scale of micro or nanometer might not be easy and practical control technique is needed. The technology of microelectromechanical systems (MEMS) has been maturely developed [336], which actuates micro or nanometer sized structure through

the electric static force and provides the solution for the metamolecule reshaping. Recently, the use of micromachined actuators is proposed for reconfiguring the metamolecule [337]. By designing the metamolecule into separated segments, the relative position of different segments can be controlled precisely. The reshape of the metamolecules tunes their THz response or switches between positive and negative permeability of the metamaterial.

The coupling between the metamolecules is demonstrated to have a strong impact on the metamaterial optical properties. The coupling is usually tuned by changing the distance between the metamolecules. In the multi-layered metamaterial, the distance change can be implemented by directly shifting different layers. [338-343]. A resonant frequency shifting is experimentally observed in microwave spectrum by shifting alternative layers of the metamaterials [341]. The distance between layers can also be compressed by an electromagnetic force due to the metamaterial's coupling with the incident light [344]. This compression can be tuned by changing input powers. The metamolecules in such design can be scaled down easily to increase the operating frequency.

For single layered metamaterial structure, the inter-metamolecule coupling can be tailored by moving individual metamolecule either in plane or out of plane. The in-plane movement through a micromachined actuator changes the symmetric and isotropic properties of the metamaterial [345, 346]. As reported in [345], the metamaterial is switched between isotropic and anisotropic state in THz regime, which tunes the polarization dependence conditions and can be applied in the birefringence switching in the metamaterial. The thermal actuator, on the other hand, are utilized to move

metamolecules out of the original plane [155, 347, 348]. The thermal expansion deforms structure composing of materials with different thermal expansion coefficients. The structure distortion is then realized through different thermal expansion. As reported in [347], different thermal expansions on two attached layers lift up the micrometer scaled metamolecules, which change their coupling as well as the orientation to the incident wave. The transmission is thus effectively modulated.

For nanometer sized actuation, the molecule reconfiguring requires much precise control which is not satisfied by the traditional tuning methods. The optical force [349-351] and Casimir force [352-354] in the metamaterial have been investigated. These two forces have a scale of piconewton and rely on the incident wave and the material structures [350, 355]. Therefore, designs of tunable metamaterial controlled by optical or Casimir forces can be further utilized for optical frequency tuning.

2.5 Summary

Based on the literature survey presented, metamaterials are the artificial materials which are promising for the electromagnetic wave control and manipulation. The propagation direction, amplitude, phase and polarization states of the wave can be effectively tailored through different approaches like the optical pumping, thermal control and electric bias on the metamaterial substrate for nonlinear effect excitation. Such manipulation methods have been widely demonstrated from microwave frequency to optical visible light regime. Particularly, the control on terahertz wave through tunable metamaterial offers a promising way for the wave modulation and helps to fill the THz gap. Metamaterial with flexible substrate changes the metamaterial property by extending, shrinking or rolling the whole metamaterial structure. On the other hand, the metamaterial property can also be tuned through every metamolecule reconfiguration, which tailors the resonance of the metamolecule effectively. The reconfiguring metamolecule in micrometer or nanometer scale can be effectively realized through micromachined processes. Meanwhile, the compatibility between micromachine processes and CMOS processes allows this tuning mechanism easy for large integration and massive production. Therefore, the demonstration of the magnetic response, electric response and the couplings between electric field and magnetic field of the EM wave in the micromachined metamaterial is of high interest for research.

CHAPTER 3

MAGNETIC RESPONSE TUNABLE METAMATERIALS

This chapter presents the design, fabrication and experiment of a reconfigurable metamaterial for the excitation and manipulation of magnetic resonance in terahertz regime of the electromagnetic (EM) wave. Magnetic resonance has been widely reported to control the refractive index or effective impedance of metamaterials. The magnetic resonance induced negative refractive index is essential for applications like superlens or invisible cloaking. The impedance matching through magnetic coupling are also applied for perfect absorbers and compact antennas, etc. In this chapter, the origin of the magnetic response in the metamaterial is analyzed. The dependence of the magnetic resonance on the incident angle and polarization state are discussed through numerical analysis. Metamolecule reconfiguration, which changes the relative position of the inclusion of the metamolecules, is realized through a micromachined actuator. The tunability of the reconfigurable metamaterial on the magnetic resonance is experimentally demonstrated.

3.1 Reconfigurable Magnetic Metamaterial Design

The excitation of magnetic resonance in different frequency of the EM wave has been discussed and various metamolecule designs are proposed, including the split ring resonator (SRR), slab-pairs and omega structures. The metamolecule, mostly made of conductive metal, manifests the magnetic resonance by introducing splits in the structure to magnetically excite free carriers oscillation. In the following design, a metamolecule derivative from the classic SRR structure is proposed, which not only enhances the magnetic response in THz regime, but also achieves a real time control on the magnetic resonant strength.

The classic SRR, or a planar ring structure with split(s), responds to the magnetic field when non-zero magnetic flux passing through the SRR plane. Here, we develop a new metamolecule from the SRR as illustrated in Fig. 3.1(a). The SRR at the center of the metamolecule is divided into two separated parts, noted as “[” and “]”, by two splits. Two metal slabs are replaced next to the SRR along with the two splits, which couples to both “[” and “]”.

The “[” and “]” is adhered to the dielectric substrate, while the metal slabs are designed to be suspended on the substrate. The metal slab suspension is fabricated using bulk micromachining fabrication processes, which is able to shift along the split of the SRR through a static electrostatic force as shown in Figs. 3.1(b) and (c). Due to the reconfiguration of the metamolecules, the interaction between the metamolecule and the incident wave changes, which further changes the optical response of the metamaterial to the incident wave.

Fig. 3.1 Schematic of the reconfigurable magnetic metamaterial: (a) perspective review and incidence condition; (b) the metamolecules in the initial state and (c) final state; (d) the incidence illustration under transvers electric (TE) polarization and (e) transvers magnetic (TM) polarization.

Here an electromagnetic (EM) wave is obliquely incident on the metamaterial surface at an incident angle θ on the z -axis and ϕ on the y -axis. The optical incidence in transverse electric (TE) and transverse magnetic (TM) polarization is shown in Figs. 3.1(d) and (e), respectively. In the TE polarization, the E -field of the incident wave is parallel to the metamaterial surface along x -axis, while in the TM polarization, the H -field is parallel to the surface along x -axis. The lattice constants a_x and a_y are both $60\text{ }\mu\text{m}$. The width w of all metal strips is $3\text{ }\mu\text{m}$. The length of the metal slabs is $50\text{ }\mu\text{m}$ and the size of the SRR is $40\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$. The gap g between the slab and the SRR is $2\text{ }\mu\text{m}$. The split between “[” and “]” is $20\text{ }\mu\text{m}$.

3.2 Simulation Results and Discussions

3.2.1 Numerical Calculation Method

The optical response of the metamaterial in THz regime is studied by numerically calculating reflectance spectrum under different incident conditions of light. The calculation method uses the microwave studio of Computer Simulation Technology (CST). Periodic boundary conditions are assumed by setting the boundary condition as “unit cell” which virtually repeats the modeled structure periodically in two directions up to infinity. Floquet port is used for the electromagnetic wave source and S -parameters are calculated to investigate the reflectivity of the metamaterial. The calculation algorithm of CST is based on Finite Integration Technique (FIT), which provides a universal spatial discretization scheme applicable to various electromagnetic problems. Unlike the other numerical methods, the integral form of Maxwell’s equations rather than the differential one are used in FIT as follows

$$\left\{ \begin{array}{l} \oint_{\partial A} \vec{E} \cdot d\vec{s} = - \int_A \frac{\partial \vec{B}}{\partial t} \cdot d\vec{A} \\ \oint_{\partial A} \vec{H} \cdot d\vec{s} = \int_A \left(\frac{\partial \vec{D}}{\partial t} + \vec{J} \right) \cdot d\vec{A} \\ \oint_{\partial V} \vec{D} \cdot d\vec{A} = \int_V \rho \cdot dV \\ \oint_{\partial V} \vec{B} \cdot d\vec{A} = 0 \end{array} \right. \quad (3.1)$$

where E is the electric field, B is the magnetic field, H is the magnetic flux, D is the electrical flux and J is the current density. These parameters are time dependent. A is the integrated surface and the V is the integrated volume. The frequency domain solver is

used by which Maxwell's equations are transformed into the frequency domain. In frequency domain, the solver is calculating one frequency each time and sweep dozens of frequency samples selected adaptively. For each frequency sample, the linear equation will be solved by an iterative or sparse direct solver.

3.2.2 Numerical Results on Two-split SRR structure

The reflectance spectrum on the two-split SRR structure without the two slabs is firstly studied. The incident direction is illustrated in Fig. 3.1, with the angle θ on the z -axis and ϕ on the y -axis. Both TE polarization and TM polarization are investigated where electrical field is normal to the incident plane for TE and magnetic field is normal to the incident plane for TM.

Figure 3.2(a) shows the numerically calculated reflectance spectra of the metamaterial from 0.5 THz to 1.2 THz with the incident wave under TE polarization and the angle ϕ at 0°. In the numerical simulation, the “lossy metal” model of Aluminum is used with the conductivity of 3.72×10^7 S/m. The spectrum tuning is investigated when θ is increased from 0° to 45°. Periodic envelopes are observed in the spectra with a period of approximately 0.38 THz, which is mainly due to the Fabry-Pérot (FP) effect from the metal layer and the silicon substrate. The free spectra range (FSR) of the Si substrate is analytically calculated as 0.43 THz by using the equation $\text{FSR} = c/2nL$, where c is the velocity of the EM wave in free space and equals to 3×10^8 m/s, n is the silicon's refractive index with value of 3.45 and L is the Si thickness which is 100 μm . The FSR of the Si substrate is about the same as the numerically calculated FSR of the metamaterial.

(a)

(b)

(c)

Fig. 3.2 Reflection under TE incidence at different θ and fixed $\phi = 0^\circ$: (a) reflection spectrum; (b) surface current at θ of 0° and (c) of 45° at 0.88 THz.

A resonance at 0.88 THz is observed in the reflectance spectrum as θ increases. The origin of the resonance is analyzed by investigating the electric and magnetic field of the incident wave. When θ is 0° , both the electric and magnetic field are parallel with the metamaterial surface. When θ increases, the direction and amplitude of the electrical field of the incident light remain the same, while the magnetic field is rotated with a non-zero magnetic flux passing through the metamaterial surface, the amount of which is getting larger. Therefore, the resonance at 0.89 THz is induced by the magnetic response. To further study the resonance behavior, the surface current and the magnetic field distributions on the metamolecule at the resonant frequency are compared in Fig. 3.2(b) when θ is 0° and Fig. 3.2(c) when θ is 45° . The arrows represent the instantaneous direction of the surface current which changes periodically as the incident electric and magnetic field changes. The color bar indicates the average amplitude of the magnetic field distribution. It is shown that the surface current on both “[” and “]” flow in x -direction when θ is 0° . The density is trivial compared with that when θ is 45° . This is due to weak electric field driving and no resonance is induced. In contrast, strong surface current is induced and the current directions are opposite on the “[” and “]”. This is asymmetric due to time-varied magnetic field passing through the split ring as typically discussed based on Lenz’s law.

Fig. 3.3 Phase difference on adjacent metamolecule under oblique incidence.

In addition, the surface current in adjacent unit cell in y-direction has a phase delay, which is due to the oblique incidence as interpreted in Fig. 3.3. The optical path difference at the adjacent unit cell is Δs , which relates to the lattice constant a and incident angle θ and can be expressed as

$$\Delta s = a \sin \theta \quad (3.2)$$

Therefore, the phase difference between two unit cells Δp is given by

$$\Delta p = 2\pi \frac{\Delta s}{\lambda} = 2\pi \frac{a \sin \theta}{\lambda} \quad (3.3)$$

Fig. 3.4 Surface current on two adjacent unit cells at two phases with different Δp : (a) and (b) for $\theta = 30^\circ$ with $\Delta p = 32^\circ$, (c) and (d) for $\theta = 45^\circ$ with $\Delta p = 45^\circ$ and (e) and (f) for $\theta = 60^\circ$ with $\Delta p = 55^\circ$.

where λ is the wavelength of the incident wave. The value of Δp is derived as 32° , 45° and 55° when θ is 30° , 45° and 60° at lattice constant $a = 60 \mu\text{m}$ and frequency $f = 0.88$ THz. The phase delay is confirmed by the numerically calculated surface current flow as shown in Fig 3.4. Two successive surface current distributions are compared: Figs. 3.4(a) and (b) show a phase shifted current distribution of 32° when θ is 30° ; Figs. 3.4(c) and (d) show a phase shifted current distribution of 45° when θ is 45° ; Figs. 3.4(e) and (f) show a phase shifted current distribution of 55° when θ is 60° . It is observed that the current distribution on one unit cell before the phase shifting is identical to that on the left-adjacent element after the phase shifting. For example, the current distribution on the left side SRR in Fig. 3.4(b) is the same with that on the right side SRR in Fig. 3.4(a). Therefore, the phase difference in x -direction between the unit cells are due to the optical path difference at the oblique incidence.

On the other hand, the magnetic field is always parallel to the metamaterial surface in TM polarization. There will be no magnetic response as θ increases. The electrical field of the incident wave passes through the metamaterial surface under this polarization and can also be divided into two components which are normal to and tangential with the metamaterial surface, respectively. The normal component of the electrical field does not induce resonance at this frequency. On the other hand, the tangential component induces a dipole resonance, which, however is in a higher frequency band beyond the discussed regime. The corresponding surface current at 0.88 THz (the magnetic resonant frequency in TE polarization) is shown in Fig 3.5(b). The current flows along same direction on structure “[” and “]”, which is driven by the electrical field.

Fig. 3.5 TM polarized reflection at fixed $\phi = 0^\circ$: (a) reflection spectra at different incident angle θ ; (b) surface current at θ of 45° at 0.88 THz.

The reflection spectra when ϕ is 90° and θ increases from 0° to 45° are also investigated in Fig. 3.6. The new weak resonance at 0.89 THz is due to the magnetic excitation from the increased magnetic flux normal to the surface. It has same frequency with that in Fig. 3.2(a) as the effective inductance and capacitance is the same. The magnetic field distribution and the surface current are illustrated in Figs. 3.7(a) and

Fig. 3.6 TE polarized reflection spectra at different θ and fixed $\phi = 90^\circ$.

Fig. 3.7 Induced magnetic field intensity and surface current on the two-split SRR at 0.89 THz when (a) θ is 45° and (b) θ is 45° while ϕ is fixed at 90° .

(b) for θ at 0° and 45° , respectively. The surface current flow in the same direction on the “[” and “]” with the same density when $\theta = 0^\circ$, which is parallel with the incident electric field direction and indicates an electric field driving on the free electrons. On the other hand, although the surface current is flowing in the same direction, its density is different when $\theta = 45^\circ$. This asymmetry can be interpreted as the superposition of electrically induced current and magnetically induced current.

There is no magnetic response in the TM polarization when ϕ is 90° , therefore, only electrical field driven currents dominant. The electrical field direction is oblique with the metamaterial surface and its parallel component is along y -axis. Therefore, no magnetic resonance is induced as shown in Fig. 3.8.

Fig. 3.8 TM polarized reflection spectra at different θ and fixed $\phi = 90^\circ$.

The reflectance spectra at TE polarization are also calculated at different split gap g_{split} , which increases from $5 \mu\text{m}$ to $20 \mu\text{m}$ when the incident angle θ is 45° . Fig. 3.9(a) shows the calculated spectra when ϕ is 0° . The magnetic resonance increases from

(a)

(b)

Fig. 3.9 TE polarized reflection spectra at different split with a fixed incident angle $\theta = 45^\circ$ at (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$.

0.82 THz to 0.88 THz when the split gap is increased. Fig. 3.9(a) shows the calculated spectra when $\phi = 0^\circ$. The magnetic resonance is identical to that when $\phi = 90^\circ$. The spectra under TM polarization is not discussed as there is no magnetic resonance here.

By looking into the magnetic resonances induced on the two-split SRR under different incident angles, it can be concluded that the resonant frequency is identical for the same structure with the same geometric size. In this design, magnetic resonance is induced at 0.88 THz when ϕ is either 0° or 90° with a nonzero θ . This is because the resonant frequency is decided by the effective inductance and capacitance of the structure, which can be modeled using an electric LC circuit as shown in Fig. 3.10. Based on this model, the AC source is the induced electromotive force from the interaction between the time varying magnetic field and the two-split SRR. The structures “[” and “]” behave as the inductor L which induces the inductor impedance of $j\omega L$. The split between the structures “[” and “]” introduces the capacitance C which corresponds to a capacitor

impedance of $\frac{1}{j\omega C}$. The resonant angular frequency ω_r is expressed as

$$\frac{1}{j\omega_r C} + j\omega_r L = 0 \quad (3.4)$$

and $\omega_r = \frac{1}{\sqrt{LC}}$ is derived. Therefore, the magnetic resonant frequency is the same for

identical effective capacitance and inductance.

Fig. 3.10 LC circuit model of the two-split SRR structure.

Investigating the magnetic resonance at different incident angle under TE polarization (there is no magnetic resonance under TM polarization), the magnetic flux passing through the metamaterial surface increases when θ is increased. This means that only AC voltage will increase with higher θ while effective capacitance and inductance remain unchanged. As a result, the magnetic resonance frequency does not change while the resonant intensity increases when θ increases, which are consistent with the results in Figs. 3.2(a) and 3.6.

Different split gap of the SRR, however, results in different effective capacitance and inductance. The capacitance is inversely proportional to the split d as $C \propto \frac{1}{d}$ while the inductance is proportional to the SRR width in x -direction $(2b + d)$, where b and d is indicated are Fig. 3.1. The resonant frequency can be expressed as

$$\omega_r \propto \frac{1}{\sqrt{LC}} \propto \sqrt{\frac{d}{2b+d}} = \sqrt{\frac{1}{\frac{2b}{d}+1}} \quad (3.5)$$

As a result, ω_r increases with d , which is consistent with that shown in Fig. 3.9.

3.2.3 Numerical Results on SRR-Slab Structure

The SRR structure discussed above induces a magnetic resonance at THz range when a TE polarized light is obliquely incident on the metamaterial surface. However, the calculated resonance from the two-split SRR is very weak due to weak coupling between the structure “[” and structure “]” and the energy is not well confined in the metamolecules. To enhance the coupling effect, the two-split SRR structure is modified by placing two metallic slabs beside the two sides of the SRR split as shown in Fig. 3.1. The slabs are not only used to serve as a “bridge” for the coupling enhancement, but also offer a way to control the magnetic resonance in real time when the relative position of the slabs to the SRR is changed.

The reflectance spectrum is numerically calculated at different slab length starting from 0 to the side length of the SRR of 50 μm as shown in Fig. 3.11. This calculation shows the modification process on the magnetic resonance when the metamolecule changes from the two-split SRR structure to the slab-SRR structure. The slabs are centrally aligned with the SRR when the length is increasing. The THz wave is incident obliquely with $\theta = 45^\circ$ and (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$ under TE polarization. It is found that the magnetic resonance strength is increased when the length of the two metal slabs increases. The resonant strength is defined as the difference of the reflectivity between the magnetic resonant dip and the adjacent peak, and noted as Δr . Meanwhile, the dip frequency f_r is red shifted.

(a)

(b)

Fig. 3.11 TE reflection spectra at different slab length at $\phi =$ (a) 0° and (b) 90° .

The change of Δr and f_r are plotted in Fig. 3.12. The dip frequency f_r for $\phi = 0^\circ$ and $\phi = 90^\circ$ are almost the same for the same slab length. This is because the effective

capacitance and inductance are the same for the same structured metamolecule. The decreasing of the f_r as slab length increases can be interpreted using the LC model of the slab-SRR metamolecule which is illustrated in Fig. 3.13. This model differs with the circuit for the two-split SRR structure by adding two new capacitors C_{slab} . The two capacitors are due to the capacitance between the slabs and the SRR, and are parallel with the capacitor C_{split} due to the SRR splits. The capacitance of a capacitor is expressed as $C = \frac{A}{\epsilon d}$, where A is the effective area of the capacitor and d is the gap between the two plates of the capacitor. Here, the effective area and the gap of C_{slab} are proportional to its length L_{slab} and the gap between the slab and the SRR g_{slab} correspondingly. Therefore, C_{slab} is getting larger as L_{slab} increases, and the total effective capacitance increases. As a result, the resonant frequency f_r decreases.

Fig. 3.12 Tuning of magnetic resonant frequency (solid line) and strength (dashed line) at $\phi = 0^\circ$ (black line) and $\phi = 90^\circ$ (red line).

Fig. 3.13 LC model of the metamolecule.

(a)

(b)

Fig. 3.14 Surface current on the slab-SRR structure at 0.75 THz under TE polarized incidence at $\theta = 45^\circ$ and (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$.

The resonant strength Δr increases from 0.02 to 0.40 when $\phi = 0^\circ$ while from 0.02 to 0.20 when ϕ is 90° . The strength increasing is due to the increased coupling between the SRR and the slabs. The coupling effect is illustrated from the surface current distribution on the slab-SRR structure as shown in Fig. 3.14 when (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$. For both incident conditions, a circular current is induced which are coupled from “[” to the slab on one side, and then coupled to “]” and finally coupled to the slab on the other side. Comparing to the two-split SRR structure with no slabs, the resonant energy is better confined and therefore the resonant strength is increased.

It's also found that the FP resonant dip is red shifted at $\phi = 0^\circ$ while remains almost unchanged at $\phi = 90^\circ$ when the slab length increases. This is because the electrical field of the incident wave is parallel to the slabs when $\phi = 0^\circ$ while perpendicular to the slabs when $\phi = 90^\circ$. The electrical dipole resonance is easy to be excited when the electrical field is parallel to the metal slabs ($\theta = 0^\circ$). This interaction effectively increases the optical path when the incident wave propagates through in the metamaterials. Therefore, a red shift for the FP resonance is observed. On the other hand, the electrical field can not drive the electron to oscillate in this relative low frequency regime when it is perpendicular to the metal slabs, and thus the FP resonance is not quite affected.

The incident angle dependence of the SRR-slab metamolecule is calculated when θ is increased from 0 to 45° as shown in Fig. 3.15. Under TE polarized incidence, the magnetic resonance is observed at 0.78 THz as θ increases. The resonant intensity is getting stronger which is the increased magnetic flux passing through the metamaterial surface. The resonant dip frequency does not change much as there is no change in the structure.

(a)

(b)

Fig. 3.15 TE polarized reflection spectra of the slab-SRR structure at different incident angle θ with (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$.

When the resonance on the SRR-slab structure inevitably linked with the couplings between the SRR and the slab, the frequency and strength of the resonance can therefore be effectively tuned by changing the coupling between the SRR and the two slabs. One approach is to change the gap width between the SRR and the slabs. The reflectance spectra are calculated when the gap increases from 2 μm to 4 μm as shown in Fig. 3.16. The light is in TE polarization incidence and θ is 45° with (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$. The magnetic resonance is significantly blue shifted as the gap increases, which is because the effective capacitance between the SRR and slabs decreases. The resonant strength, on the other hand, decreases significantly when the slab gap increases. This is because the coupling between the SRR and the slabs are decreased when g_{slab} increases.

The metamolecules can also be reconfigured by moving the slabs along y -axis to change the coupling effect between the SRR and the slabs. The movement can be driven by the micromachined actuator. The lattice constant of the unit cell is 60 μm , and the unit cell is a symmetric structure. Therefore, the tuning is the same for every 30 μm shifting. The reflection spectra at different slab shifting distances Δs are plotted in Fig. 3.17. Initially the magnetic resonance is excited at 0.77 THz. As the slabs are displaced, the magnetically induced current coupled between the “[” and “]” of the SRR is sharply decreased. As a result, the magnetic resonance becomes weak. In addition, the capacitance between the SRR and the slabs are decreased when the slabs shift from the original state to the final state as shown in Fig. 3.1(c). Therefore, the effective capacitance of the structure decreases and the resonant frequency increases.

(a)

(b)

Fig. 3.16 TE polarized reflection at different slab gap at θ of 45° and (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$.

(a)

(b)

Fig. 3.17 TE polarized reflection spectra of the slab-SRR structure at different shifting displacement at (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$ at θ of 45° .

To further understand the resonance tuning due to the slab shifting, the surface current at 0.74 THz on the SRR-Slab structure when Δs is 30 μm are plotted as shown in Fig. 3.18. No asymmetric current is induced at this state, indicating that the magnetic excitation in the initial state is suppressed. The surface currents cannot couple from structure “[” to “]” structure through the slabs. Only small current is induced by the electric field on the SRR along x -direction when $\phi = 0^\circ$ (Fig. 3.18(b)) and on free-hanging slabs along y -direction when $\phi = 0^\circ$ (Fig. 3.18(d)).

Fig. 3.18 Surface current on the metamolecule in (a) the initial state and (b) the tuned state at 0.74 THz.

3.3 Fabrication Processes

3.3.1 Micromachined Actuator Design and Fabrication

The suspended slabs are in-plane bidirectionally actuated through the micromachined electrostatic comb driver while the two-split SRR is anchored on the substrate. The micromachined comb driver designed is illustrated in Fig. 3.19. The comb driver consists of four pairs of stationary set and the movable set. In each pair, comb fingers on the stationary set and movable set are designed faced each other. Therefore, as illustrated in Fig. 3.19(a), the movable set moves forward when electric voltage V_f is applied and moves backward when V_b is applied due to the electrostatic forces between the two plates. The slabs are connected with the suspension beam in the center and driven by the movable set actuation bidirectionally.

The SEM graph of the comb drive is shown in Fig. 3.20, the connection beam connects to the movable comb set and is driven by the electrostatic force when electric bias is applied. When a DC voltage V is applied between the movable comb and stationary comb, the two combs attract each other and the movable comb moves to the stationary comb with a displacement Δx . The mechanical restore force is then induced to balance the electrostatic force. The displacement can be expressed as [356]

$$\Delta x = \frac{n\epsilon t}{gk_x} V^2 \quad (3.6)$$

where n is the comb figure pair number, ϵ is the dielectric constant of the medium, t is the thickness of comb fingers, g is gap between fingers on the same set and k_x is the suspension beam stiffness. The stiffness depends on the suspension beam material and geometries and can be expressed as [356]

$$k_x = \frac{2EtW_b^3}{L_b^3} \quad (3.7)$$

where E is the Young's modulus of the silicon material, L_b and W_b are the length and width of the comb finger, correspondingly. Therefore, the movable comb set displacement can be expressed as

$$\Delta x = \frac{n\varepsilon}{2Eg} \left(\frac{L_b}{W_b} \right)^3 V^2 = KV^2 \quad (3.8)$$

Fig. 3.19 Schematic graph of the comb drive in (a) top view and (b) perspective view.

where K is the actuation coefficient with the value of 0.04 in the design. Therefore, the displacement Δx is proportional to the voltage square and it can be calculated that a bias voltage about 27 V is required to obtain an actuation distance of 30 μm .

(a)

(b)

Fig. 3.20 SEM graph of the comb drive in (a) perspective view and (b) top view.

3.3.2 Silicon Deep Etching Processes

The metamaterial is fabricated on a Silicon-on-insulator (SOI) wafer which consists of three layers. The bottom is the Si substrate layer. The middle layer is made of insulator SiO_2 layer. The top layer is a single crystal Si layer called the structure layer. The SOI wafer is commonly used in MEMS fabrication processes, which is fabricated to reconfigure metamaterial elements.

The processes flow for the micromachined metamaterials are illustrated in Fig. 3.21. The processes starts with a cleaned SOI wafer as in Fig. 3.21(a). A 500 nm thick aluminum is deposited on the device layer of the SOI wafer using physical vapor deposition (PVD) process as shown in Fig. 3.21(b). The aluminum layer functions have two functions: one is to be patterned as the metamolecule structure in next steps and the other is to be used as the metal contact for the micromachined actuator. Followed by the metal deposition, the SOI wafer has to be cleaned to avoid fabrication chamber contamination in the next steps. The metal structure is then patterned using lithography processes. The aluminum layer is coated with 600 angstrom BARC (Bottom Anti-Reflection Coatings) and 1- μm -thick photoresist as shown in Fig. 3.21(c). The BARC is to enhance the uniformity when patterning the structure of the metal in the next step. The photoresist coating is a spin coating process which dispenses the viscous photoresist on the wafer and produces a uniform layer through wafer spinning. The photoresist is then prebaked, followed by exposing it under a patterned intense light source with a predesigned mask between the source and the wafer as shown in Fig. 3.21(d). The exposed photoresist undergoes a chemical change during the shining, which can be removed through the develop procedure and leaves the non-exposed part as shown in Fig.

3.21(e). A microscope check on the photoresist pattern is usually necessary to confirm the structure, which may be over developed or misaligned. The BARC is then opened followed by aluminum etching and photoresist strip as shown in Fig. 3.21(f). After the patterning of the metamolecule structure and metal contact pad, the next steps are to separate the movable structures from the fixed ones. Therefore, the device layer between the structures needs to be etched. Another round of lithography process is then carried out as shown in Figs. 3.21(g) and (h). The device layer is etched through till the box layer, the etching depth is 75 μm . Here, DRIE process is used to realize high anisotropic etch with high aspect ratio. As the etching ratio between the photoresist and the device layer is about 1:10, a photoresist layer as thick as 10 μm is deposited for the lithography process. The DRIE involves both polymer deposition and silicon etching which protects the side wall while etching the device layer vertically, the process of which is name as Bosch process. The etching time takes about 42 mins to completely reach the box layer as shown in Fig. 3.21(i). Descum process is performed for about 5 mins to remove the polymers generated during the DRIE process. The covered photoresist is removed and now the device layer is etched and the slabs and the bulk structure are separated on the box layer (Fig. 3.21(j)). HF vapor is then used to etch the box layer isotropically. The etching time is well-controlled so that the box layer under the slabs structure is fully etched while the one under the bulk structure is only partially etched as shown in Fig. 3.21(k). This etching difference is guaranteed by the fact the etching of the box layer under the slabs takes much less time than that under the bulk structure. The slabs and the movable comb drives are then suspended on the substrate layer.

Fig. 3.21 Processes flow of micromachine deep etching: (a) SOI wafer; (b) Al deposition; (c) PR coating; (d) lithography exposure; (e) photoresist developed; (f) Al etching; (g) lithograph exposure for device layer etching; (h) photoresist develop for device layer; (i) DRIE process; (j) photoresist strip; (k) BOX layer released.

Fig. 3.22 SEM graph of the micromachined tunable metamaterial

The scanning electron microscopic (SEM) image of the fabricated micromachined metamaterial is shown in Fig. 3.22. It consists of a 200×200 metamolecule array which has an in-plane translational period of $60 \mu\text{m}$ in x and y direction. Fig. 3.22(b) shows the close-up view of the metamolecule structure, which is formed by patterning a $0.5\text{-}\mu\text{m}$ thick aluminum layer on the top of the silicon structures. The free-hanging slabs with a length of $50 \mu\text{m}$ are patterned on the $3\text{-}\mu\text{m}$ wide frame. The SRR is a $40 \mu\text{m} \times 50 \mu\text{m}$ rectangular ring and patterned on the isolated anchors. Since each anchor encloses a larger area of the underlying oxide layer than the frame, the oxide under the anchor still remains when it is all removed under the frame. As a result, the supporting frame is fully released and becomes freely movable while the anchor remains fixed on the substrate. The supporting frame is connected to the micromachined comb drive actuator, which

provides bidirectional in-plane translation (along the y-direction) up to 30 μm driven by the electrostatic force.

3.4 Experimental Results and Discussions

3.4.1 Experimental Setup

Experimental setup for the THz wave measurement of the tunable metamaterial is Fourier transform infrared spectroscopy (FTIR) (Bruker Vertex 80v) as shown in Fig. 3.23. The FTIR mainly consists of three parts: (a) the IR laser source and the beam splitter, which generate an interferogram and provide the THz signal; (b) the sample chamber where the sample is placed for measurement and (c) the detection components which transmit the detected signal to computer for analysis.

Fig. 3.23 Fourier transform infrared spectroscopy for THz spectra measurement.

The essential component of the interferogram generator is a Michelson interferometer as shown in Fig. 3.24. The beam splitter of the interferometer ideally

transmits 50% of the light and reflects the remaining part. The two parts of the light have an optical path difference $2\Delta x$ which depends on the movable mirror M2. The interference of the two parts of the light depends on the optical path difference. For a single wavelength signal, the light intensity at the detector can be expressed as

$$I(x) = S(\nu) \cos(2\pi\nu x) \quad (3.5)$$

where ν is the wavenumber which equals to $\frac{1}{\lambda}$ and $S(\nu)$ is the intensity of a monochromatic spectral line at wavenumber ν . Replacing the continuous path difference x and wavenumber ν to discrete value $n \cdot \Delta x$ and $k \cdot \Delta \nu$, the discrete Fourier Transform of the spectrum intensity can be expressed as

$$S(k \cdot \Delta \nu) = \sum I(n \cdot \Delta x) \exp(i2\pi nk / N) \quad (3.6)$$

where $N\Delta x$ is the total moving distance of mirror M2.

Fig. 3.24 Michelson interferometer in the FTIR.

(a)

(b)

Fig. 3.25 Experimental setup for the reflection measurement using FTIR: (a) reflection module of FTIR and (b) optical path for the reflection measurement.

The reflection setup module is shown in Fig. 3.25(a) and the optical path for the reflection measurement is illustrated in Fig. 3.25(b). The light beam is incident onto M1 and reflected onto the sample through M2. The light reflected from the sample

propagates through mirror M3 and M4 and is received by the detector. The incident angle θ can be tuned by mechanically rotating M2 and M3 from 15 ° to 75 °.

3.4.2 Experimental Results and Discussions

The reflection spectra of the metamaterial are measured when the incident angle θ increases from 15 ° to 45 ° with ϕ fixed at 0 ° and 90 °, respectively. In the reflection module, the measurement for normal incidence is not available due to the limit of FTIR setup. When $\phi = 0^\circ$, wide dips are observed in the reflection spectra for θ of 15 °, 30 ° and 45 ° in the spectrum from 0.65 THz to 0.9 THz as shown in Fig. 3.26 (a). These dips are due to the FP resonance of the substrate. Besides the FP resonance, no resonant mode is excited when $\theta = 15^\circ$. Theoretically, due to this oblique incidence, there is non-zero amount of time-varying magnetic flux passing through the metamaterial surface. However, the value of the flux B is related with the incident angle as

$$B \propto \sin \theta \quad (3.7)$$

Therefore, the magnetic flux is small at a small incident angle and not enough to induce a significant observable magnetic resonance. When θ increases from 15 ° to 30 °, or $\sin \theta$ increases from 0.26 to 0.50, the magnetic resonance is observed at 0.76 THz with a resonant peak of 25%. When θ is further increases to 45 °, $\sin \theta$ increases to 0.71 and the resonant peak reaches 30% at the same frequency. A similar resonance excitation is also observed when $\phi = 90^\circ$ as in Fig. 3.26(b). The resonance is not observed in the spectrum range when $\theta = 15^\circ$ while is induced at θ of 15 ° and 30 ° with a resonant

Fig. 3.26 Comparison of measured (left column) and simulated (right column) reflection spectra at (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$ when $\theta = 15^\circ$ (black line), $\theta = 30^\circ$ (red line) and $\theta = 45^\circ$ (blue line).

Fig. 3.27 Measured reflection spectra at (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$ and $\theta = 45^\circ$ when slab shifting $\Delta s = 0 \mu\text{m}$ (black line), $\Delta s = 15 \mu\text{m}$ (red line) and $\Delta s = 30 \mu\text{m}$ (blue line).

strength of 15% and 21% correspondingly at 0.76 THz. The resonant frequency is not changed and the resonant strength is increased as θ increases, which is due to the magnetic excitation as analyzed. The measured resonant frequency well agrees with the simulation results while the resonant strength is weaker than that in the simulation. This is mainly due to the losses in the substrate which could be improved by using a low loss substrate.

The reflection spectra change when the slabs are shifted by the comb drive. These are characterized by measuring $\Delta s = 0 \text{ }\mu\text{m}$, $15 \text{ }\mu\text{m}$ and $30 \text{ }\mu\text{m}$ as shown in Fig. 3.27. The corresponding electrical bias applied are 0 V, 20 V and 27 V to realize the slab shifting. The magnetic resonance at 0.76 THz in the initial state under an oblique incidence with $\theta = 45^\circ$ are observed to be suppressed when the metal slabs are shifting by $15 \text{ }\mu\text{m}$ and $30 \text{ }\mu\text{m}$. The reflection at 0.76 THz is decreased from 30% to 15% during the slab shifting when $\phi = 0^\circ$ and from 21% to 12% when ϕ is 90° as the metal slabs are shifted by $30 \text{ }\mu\text{m}$. The magnetic resonance is significantly suppressed during the metamaterial reconfiguration, which is due to the weakened magnetic coupling between the metamolecule and the incident wave.

3.5 Summary

This chapter focuses on the excitation and manipulation of the magnetic resonance in a reconfigurable metamaterials: the magnetic response is enhanced in a modified SRR metamolecule and the resonant intensity is tailored through metamolecule reshaping. The resonance in the reflectance spectrum are analyzed through both numerical method and *LC* circuit model. The resonant frequency and intensity are compared in different incident condition to characterize the magnetic response of the metamaterial. The origin of the resonance is studied by investigating the induced magnetic field and surface current on the metamolecules. The approach to enhance and control the magnetic response in a two-split SRR is proposed by applying two metal slabs beside the SRR structure. A micromachined fabrication process is developed to reconfigure the metamolecules. The performance of the metamaterial is experimentally characterized by measuring the reflectance in different incident angle and different reconfigured states using an FTIR system.

The novelties of the magnetic response tuning in a reconfigurable metamaterial are summarized as follow,

- a) The dependence of the metamaterial magnetic response on the incident conditions are comprehensively studied and analyzed through both numerical calculation and analytical modeling. The magnetic resonance interpreting method offers a way to predict the magnetic resonant frequency and intensity, which is also applicable on other types of metamolecules.

- b) A structure modification is proposed on a typical SRR metamolecule, which enhances the magnetic coupling between the metamaterial and the incident THz wave.
- c) A micromachined process is developed which reconfigures the metamaterial to effectively tune the magnetic response in terms of resonant frequency and intensity.

CHAPTER 4

ELECTRIC RESPONSE TUNABLE METAMATERIALS

This chapter presents the design, fabrication and experiment of a reconfigurable metamaterial for electric response tuning in THz regime. Two different designs of metamaterial are presented to tune the electric response of optical wave through different coupling mechanisms, which include destructive interference, capacitive coupling and conductive coupling between the optical resonators. The electric response tuning is investigated both numerically and analytically. A resonant peak in reflective spectrum is controlled through the element structure reconfiguration. The capacitive coupling is tuned by changing the distance between the resonators which is driven by micromachined actuators. The conductive coupling is induced by getting two resonators contacted which provide switching function on the electric resonance.

4.1 Tunable Electric Metamaterial for EIT-like Effect

As reviewed in Section 2.2.2, the electromagnetically induced transparency (EIT)-like effect in the metamaterial is the phenomenon of extraordinary transmission induced by the destructive interference between a radiative mode and a non-radiative mode. The interference largely depends on the couplings between the two modes. In fact, the EIT effect in the classical optical physics does not have to be limited in the transmission spectrum. Here, the EIT-like effect is demonstrated in the reflection spectrum of an electric responded metamaterial. The radiative and non-radiative modes in the metamolecule destructively interfered with each other. The destructive coupling in the metamolecule is dynamically tuned through a micromachined element reconfiguration.

4.1.1 Tunable EIT-like Metamaterial Design

The planar metamaterial usually only responses to the electric field of the incident wave when the wave is incident onto the metamaterial surface as per normal. Comparing with the magnetic response, the electric responses are usually easy to be excited. The free electrons on the metal structure are driven to oscillate due to the electrical force. Such resonance is also governed by the structure, shape and arrangement of the metamolecule and therefore can be effectively controlled through the reconfiguration of the metamolecule.

On the other hand, to realize an EIT-like effect in the electric responded metamaterial, two types of resonators are required in the metamolecule: (a) the resonator directly responding to the electric field, and (b) the resonator not responding to the

Fig. 4.1 Schematic of the electric response tunable metamaterial: (a) perspective review of the metamaterial; (b) the initial state; (c) the middle state and (d) the final state of the metamolecule.

electric field. Here the electric metamaterial for the EIT-like effect shares the same structure with that in Chapter 3, in which magnetic response is tuned under oblique incidence. In this chapter, only electric response is focused with a normal incidence. The metamaterial consists of a two-split SRR and two movable slabs as illustrated in Fig. 4.1(a) with electric polarization along the x -axis. The lattice constant of the unit element is $60 \mu\text{m}$, the slab length is $50 \mu\text{m}$ and the gaps between the SRR and the slabs are $2 \mu\text{m}$. As the electric field is along the element structure “[” and “]”, while perpendicular to the slabs, the optical responses of the two types of resonators are different. The two responses

are coupled with each other and the coupling can be tuned through the metamolecule reconfiguration from the initial state (Fig. 4.1(b)) to the middle state (Fig. 4.1(c)) with the slabs shifted along the y -direction for a quarter of the lattice constant, and to the final state (Fig. 4.1(d)) with the slabs shifted for one half of the lattice constant.

4.1.2 Numerical and Analytical Results and Discussions

The reflection spectrum of the “two-split SRR + substrate” and the spectrum of the “metallic slabs + substrate” are numerically calculated from 2.15 THz to 2.35 THz as shown in Fig. 4.2. The THz wave is normally incident on the metamaterial with incident electrical field in x -direction as in Fig. 4.1(a). Two dips are induced: at 2.26 THz for the two split SRR and 2.24 THz for the metal slab. The two resonant dips are investigated through the induced magnetic field and the surface current flow on the metallic structure of the metamolecule as shown in Figs. 4.3(a) and (b). The induced magnetic field strength is proportional to the surface current density on the metallic structure and the strength is indicated using the color bar. The direction of the surface current flow is time varied due to the time-changing incident electric field, the black arrows show an instantaneous flow direction of the current. In the SRR structure, the

Fig. 4.2 Reflectivity of the SRR structure (black line) and the slab structure (red line).

surface currents on both structures “[” and “]” flow in the same direction, and are parallel to the incidence electric field. The resonance is a dipole mode on the metamolecules. However, the currents are formed in the way that they concentrate on the two ends of the structure “[” or “]” with a weak amplitude in the center. Therefore, the dipole mode is formed at 2.26 THz on the two-split SRR with a high order resonance. In addition, the resonant dip is also affected by the substrate [357]. On the slab structure, the induced surface current is almost zero compared to that on the SRR structure. The corresponding dip observed in the slab structure is wider than that of the two-split SRR because less wave is reflected in the non-radiative mode and the dip is mainly due to the FP resonance of the substrate.

Fig. 4.3 Magnetic field and surface current (a) on the two-split SRR at 2.26 THz and (b) on the metal slabs at 2.24 THz.

When combining the two-split SRR and the slabs, their responses to the electric field of THz wave couple with each other. The coupling in the combination, or the SRR-slab metamolecule, could be tuned by changing the relative position of the slabs to the SRR. The slabs are initially located at the face-to-face side of the “[” and “]” structure as shown in Fig. 4.1(b). The metal slabs are shifted by the micromachined actuators with a

Fig. 4.4 Reflectivity spectra of the metamaterial when the slabs shift by a displacement from 0 μm to 30 μm .

displacement Δs up to 30 μm . The reflectivity of the metamaterial at different Δs is shown in Fig. 4.4. Compared to the reflectivity of the two-split SRR metamaterial (Fig 4.2 black line), a resonant peak is induced at 2.28 THz when the slabs are added in the initial state. The resonant peak is suppressed during the slab shifting and totally suppressed when Δs reaches 15 μm as shown in the left column of Fig. 4.1(c). The resonant peak is observed again as the slab shifting continues and reaches maximum at Δs of 30 μm (Fig. 4.1(d)). In the entire slab shifting process, the incident direction remains normal and the incident magnetic field is parallel to the metamaterial surface. Therefore, the resonance is only due to the electric response of the slab-SRR metamaterial to the incident THz wave. The resonant strength can be effectively tuned by moving the metal slabs along the y -direction which reconfigures the metamolecule structure.

The induced magnetic field and the surface current flow on the slab-SRR metamolecule are investigated when the slabs shift for Δs of 0 μm , 15 μm and 30 μm as shown in Figs. 4.5(a), (b) and (c), respectively. The color bar is the same in Figs. 4.2 and 4.5. The solid arrows indicate strong surface currents while the dashed arrows indicate the weak ones.

In the initial state, the surface current on the SRR is much smaller than that on the SRR when there is no metal slabs. On the other hand, strong surface current is induced on the slabs. As the slabs are perpendicular with the incident electric field direction, the strong current along the slabs cannot be induced directly by the electric field at this frequency, which is evidenced as in Fig. 4.3(b). Therefore, the strong surface current on the metal slabs in the slab-SRR structure is due to the coupling between the

Fig. 4.5 Magnetic field and surface current at different metamaterials states: (a) the initial state (b) the middle state and (d) the final state at 2.28 THz.

SRR and the slabs when $\Delta s = 0 \mu\text{m}$. The current on the slabs concentrates on the two ends of the slabs. The direction of the weak current on the SRR is the same when there

is no slabs. The strong current on the slabs is in the opposite direction with that on the ends of SRR.

In the middle state as in Fig. 4.5(b), the current on the SRR becomes strong which is similar to that in Fig. 4.3(a). On the other hand, the strong current on the slabs in the initial state drops dramatically. Therefore, the coupling at this state between the SRR and slabs is weakened due to the slab shifting. When the slabs continue to shift with Δs of 30 μm (Fig. 4.5 (c)), the coupling is strengthened again and the case is similar to that in the initial state. The surface current concentrates on the slabs and becomes weak on the SRR.

Fig. 4.6 Analysis of the coupling between the SRR and the slabs.

The current distribution on the metamolecule is symmetric for the structure “ $\overline{\sqcap}$ ” and “ $\overline{\sqcup}$ ”, and it is possible to analyze the coupling between the slabs and SRR by only investigating structure “ $\overline{\sqcup}$ ” as shown in Fig. 4.6, which is switched between (a) the initial state and (b) the final state. The red arrow in the figure indicates the current on structure “ $\overline{\sqcup}$ ” before the coupling, which is directly by the incident electric field. This time-varied

current on the “J” induces time-varied magnetic field on the two sides of “J”. The net magnetic field in the area between the right side of the slabs is non-zero when Δs is $0 \mu\text{m}$ (Fig. 4.6 (a)) and therefore induces a current on “ $\overline{\text{J}}$ ” to opposes the original change in magnetic flux. As a result, strong current is induced on the slabs and the current on “J” is weaken. While in the middle state, the net magnetic field induced between the two slabs are nearly zero, therefore, no current is induced on the slabs in this state and the coupling between the SRR and the slabs is weak. The resonance at this state behaves as if there are no slabs. The coupling when $\Delta s = 30 \mu\text{m}$ is similar with that when $\Delta s = 0 \mu\text{m}$ and hence not discussed repeatedly.

Fig. 4.7 EIT model for the SRR-slab metamaterial.

The coupling between the two structures is alike in the EIT interference. The EIT interference involves three quantum states: the ground state $|0\rangle$, the excited state $|1\rangle$ and the meta-state $|2\rangle$. As shown in Fig. 4.7, the free electrons in the ground state can be directly excited by the probe beam to the excited state, which cannot be directly excited

to the meta-state. As $|1\rangle$ is radiative, the excitation from $|0\rangle$ to $|1\rangle$ induces an energy absorption peak. This is similar with a reflectivity dip in the SRR structure without slabs. However, when $|1\rangle$ interferes with the non-radiative state $|2\rangle$ destructively, the absorption drops dramatically and induces a high transparency. This process is the same with the one when the SRR couples to the non-radiative slabs, and the reflectivity increases.

Fig. 4.8 Two coupled oscillator model for the SRR-slab metamaterial.

The energy absorption of the EIT system can be modeled using a two-coupled-oscillator model as shown in Fig. 4.8 [51]. This model consists of two oscillators: one is radiative and the other is non-radiative. The two oscillators have oscillating frequencies ω_{o1} and ω_{o2} which are slightly different from each other and can be expressed as

$$\begin{cases} \omega_{o1} = \sqrt{\frac{k_1}{m_1}} \\ \omega_{o2} = \sqrt{\frac{k_2}{m_2}} \end{cases} \quad (4.1)$$

where m_i and k_i are the oscillator mass and the spring constant of the spring connected to the ground. The two oscillators are coupled together with a coupling factor K . Similar to the SRR which is driven by the incident THz wave in the metamolecule, the radiative

oscillator M_1 is driven by an external force $Fe^{-i\omega t}$ which is a sinusoidal function of time. The non-radiative M_2 is not driven by external forces but can be driven to oscillate along with M_1 due to the coupling effect. The energy is coupled from M_1 to M_2 . The oscillations of M_1 and M_2 suffer losses due to the external resistance from air and other environmental factors. The damping factors of M_1 and M_2 due to the resistance are noted as γ_{o1} and γ_{o2} , correspondingly. Assume that the time-dependent displacement of the two oscillators are X_1 and X_2 , then the velocity of the two oscillators are $\dot{X}_1$ and $\dot{X}_2$, and the corresponding accelerations are $\ddot{X}_1$ and $\ddot{X}_2$. The damping force is proportional to the velocity of the oscillators which are expressed as $\gamma_{o1}\dot{X}_1$ and $\gamma_{o2}\dot{X}_2$. Therefore, according to Newton's Second Law that the total force on an object equals to the mass of the object multiplied by the acceleration of the object, the motion of M_1 and M_2 can be expressed as

$$\begin{cases} Fe^{-i\omega t} - k_1X_1 - K(X_1 - X_2) - \gamma_{o1}\dot{X}_1 = m_1\ddot{X}_1 \\ -k_2X_2 - K(X_2 - X_1) - \gamma_{o2}\dot{X}_2 = m_2\ddot{X}_2 \end{cases} \quad (4.2)$$

The Eq. 4.2 can be simplified as

$$\begin{cases} \ddot{X}_1 + \gamma_1\dot{X}_1 + \omega_1^2X_1 - \Omega_1X_2 = Ae^{-i\omega t} \\ \ddot{X}_2 + \gamma_2\dot{X}_2 + \omega_2^2X_2 - \Omega_2X_1 = 0 \end{cases} \quad (4.3)$$

where

$$\begin{cases} \gamma_i = \gamma_{oi} / m_i \\ \omega_i = (k_i + K) / m_i \\ \Omega_i = K / m_i \\ A = F / m_1 \end{cases} \quad (4.4)$$

Assuming $X_i = A_i e^{-i\omega t}$, Eq. 4.3 can be solve as

$$\begin{cases} A_1 = \frac{AH_2}{H_1H_2 - \Omega_1\Omega_2} \\ A_2 = \frac{A\Omega_2}{H_1H_2 - \Omega_1\Omega_2} \end{cases} \quad (4.5)$$

where $H_i = \omega_i^2 - j\gamma_i\omega - \omega^2$. Here j is used for the imaginary unit to avoid confusion with the subscript number i . The absorbed power of the coupled-oscillator system is calculated as $P = \text{real}(Fe^{-i\omega t})\text{real}(\dot{X}_1)$. In one period of the external force $T = \frac{2\pi}{\omega}$, the energy absorbed is

$$\begin{aligned} W &= \int_0^{2\pi/\omega} \left\{ F_0 \cos(\omega t) \text{real} \left\{ -i\omega A_1 [\cos(\omega t) - i \sin(\omega t)] \right\} \right\} dt \\ &= \text{imag} \left[\pi \frac{F_0^2}{m_1} \frac{\omega_2^2 - i\gamma_2\omega - \omega^2}{(\omega_1^2 - i\gamma_1\omega - \omega^2)(\omega_2^2 - i\gamma_2\omega - \omega^2) - \Omega_1\Omega_2} \right] \end{aligned} \quad (4.6)$$

Therefore, the non-absorbed energy can be derived as $R = 1 - W_n$, where W_n is a normalized value of W the maximum of which is less than 1. Proper value are chosen for Eq. 4.6 as shown in Table 4.1 to fit with the reflection peak in Fig. 4.3. Ω_1 and Ω_2 are set to the same value Ω for simplicity.

Table 4.1 Parameter value of the two coupled oscillator model

Parameters	Values
$\pi F_0^2 / m_1$	0.25
ω_1	2.25
ω_2	2.28
γ_1	0.12
γ_2	0.016
ω	2.15~2.35
Ω	0.08

In Table 4.1, the value of $\pi F_0^2 / m_1$ is set to 0.25 for normalization of the absorption energy. The resonance frequencies ω_1 and ω_2 are set at 2.25 and 2.28 which corresponds to the resonant dip at 2.25 THz and the induced peak at 2.28 THz of the reconfigurable metamaterial as shown in Fig. 4.3. The damping factors γ_1 and γ_2 are chosen such that radiative oscillator M_1 has a much higher loss than non-radiative oscillator M_2 . The frequencies of the external forces are set from 2.15 to 2.35 to cover the investigated frequency band. The coupling factor Ω is a variable which corresponds to the coupling between the SRR and the slab in the metamolecule. It depends on the tuning state of the metamaterials. The dependence of the non-absorbed energy on the damping factor γ_2 and the coupling factor Ω between M_1 and M_2 is investigated by independently changing their values while fixing the other parameter values.

As shown in Fig. 4.9, a wide resonant dip is observed across the frequency band from 2.15 to 2.35, which is due to the absorption from the radiative oscillator M_1 with a

high damping factor $\gamma_1 = 0.12$. A strong resonant peak is induced at 2.28 when the damping factor $\gamma_2 = 0.016$. The damping factor of oscillator M_2 is much smaller compared to that of M_1 because it is a non-radiative mode which has a low loss. When γ_2 increases, the loss of the coupled energy is also increased. The resonant peak at 2.28 is then suppressed and finally got vanished when γ_2 increases to 0.09, the value of which is comparable with that of the radiative damping factor γ_1 . This is because M_2 is changed to a radiative mode at this high damping factor, and the absorption at this frequency accordingly increases.

Fig. 4.9 Non-absorbed energy in the two-coupled oscillator model at different damping factor.

The resonant peak of M_2 also depends on the coupling between M_1 and M_2 . As shown in Fig. 4.10, there is no resonant peak when the coupling factor $\Omega = 0$. The

energy is totally absorbed by M_1 while M_2 is excluded in the oscillation system. Resonant peak is induced and getting stronger at ~ 2.28 THz when Ω increases. This is because more energy is coupled from the radiative oscillator to the non-radiative one with a larger Ω , and the total absorption of the system is lowered and the strength of the resonant peak at the non-radiative oscillator frequency increases. Correspondingly, the reflectivity peak at 2.28 THz in the SRR-slab metamaterial, is also tuned by the coupling change between the SRR and the slabs when their relative position is changed.

Fig. 4.10 Non-absorbed energy in the two-coupled oscillator model at different coupling factor.

4.1.3 Experimental Results and Discussions

Both reflection and transmission module of the FTIR spectrometer (Bruker Vertex 80v) are used to measure the reflectivity and transitivity of the SRR-slab metamaterial in different states as shown in Figs. 4.11(a) and (b), respectively. The Gauss-like envelopes in the spectra are induced by the FP resonance of substrate with a period of about 0.4 THz. The measurement on the reflectivity under normal incident is not available due to the setup limit of the system, and here it is measured with a small incident angle 15° . Although magnetic flux passes through the metamaterial surface plane, as discussed in Chapter 3, the induced magnetic response is trivial at this small angle and therefore we can still consider the measured reflectivity as the spectrum with only electric response. In the reflectivity spectrum, a resonant peak at 2.22 THz is observed in the initial-state ($\Delta s = 0 \text{ } \mu\text{m}$) because the resonant energy on SRR is coupled to the unexcited free-hanging slabs. The resonant peak at 2.22 THz is switched off when the metamaterial is tuned to the middle state ($\Delta s = 15 \text{ } \mu\text{m}$) and the coupling between SRR and free-hanging slabs becomes weak. As the metamaterial is further tuned from the middle to the final state ($\Delta s = 30 \text{ } \mu\text{m}$), the resonant peak is induced again due to the increased coupling. The transmittivity spectra of the metamaterial are measured under normal incidence, therefore have a small shift in frequency compared to the reflectivity spectrum.

(a)

(b)

Fig. 4.11 Experimental results of the (a) Transitivity and (b) reflectivity of the SRR-slab metamaterial.

4.2 Capacitive Coupling Tunable Metamaterial

4.2.1 Capacitive Coupling Tunable Metamaterial Design

The tuning of the EIT-like effect is discussed in Section 4.1, which manipulates the electric response coupling factor between a radiative resonator and a non-radiative resonator. In this section, the capacitive coupling of the electric responses are tuned by changing the distance between the resonators in the metamolecules. The effective capacitance and radiative loss of the metamolecule are effectively controlled so that the resonant frequency and the strength of the metamaterial resonance is tailored. In addition,

Fig. 4.12 Schematic of the capacitive coupling tunable metamaterial: (a) perspective review; (b) metamolecule before switching; (c) metamolecule after switching.

conductive coupling between the resonators is switched between the OFF state and the ON state, where the resonators in the metamolecule are separated and contacted, respectively. The conductive coupling alters the resonant condition and realizes a high switching ratio. The electric response metamaterial consists of three metallic strips as shown in Fig. 4.12(a). The strips on the two sides are along the x -direction and the strip in the center is along the y -direction and they are named accordingly as the left-strip, the center-strip and the right-strip, respectively. The left-strip is suspended on the substrate while the center-strip and the right-strip are fixed on the substrate. The suspended left-strip can be driven by the micromachined actuator in the x -direction. The metamolecules have a unit cell constant of $45\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$. When electrical bias is applied on a MEMS actuator, the movable left strip shifts to right and finally conducts with the center-strip as shown in Fig. 4.12(c).

4.2.2 Simulation Results and Discussions

The transmission spectra of the strip contactable metamaterial is numerically calculated using CST microwave studio for the normal incident with different polarizations. Firstly, the spectra of the metamolecule with single x-strip are calculated in the x -polarized and y -polarized incidence from 2.70 THz to 3.10 THz as shown in

Fig. 4.13 Transmittivity of the single-x-strip metamolecule: (a) schematic of the metamolecule; (b) transmittivity spectrum.

Fig. 4.13. The strip is modeled using Al with size of $12\ \mu\text{m}$ long, $6\ \mu\text{m}$ wide and $200\ \text{nm}$ thick. The unit element constant is $45\ \mu\text{m} \times 25\ \mu\text{m}$ with a $100\ \mu\text{m}$ thick silicon substrate. A strong resonant dip is observed at $2.86\ \text{THz}$ for x -polarization while no resonance is induced for the y -polarization.

Fig. 4.14 Magnetic field intensity in the single- x -strip under different polarization: (a) x -polarized incidence and (b) y -polarized incidence at $2.86\ \text{THz}$.

The surface current on the x -oriented strip is plotted at $2.86\ \text{THz}$ for both x -polarized incidence (Fig. 4.14 (a)) and y -polarized incidence (Fig. 4.14 (b)). Strong surface current is induced on the metal strip under x -polarized incidence. The free electron oscillation in the metallic strip induces a secondary wave which cancels the primary incidence and induces a resonant dip. On the other hand, the surface current is

much weaker under y -polarized incidence as at this frequency the free electrons do not resonate along the y -direction in such a short path. The secondary wave is then too weak to cancel the primary incident wave.

The resonant frequency and strength of the single- x -strip metamaterial under x -polarization incidence is dependent on the metal strip length. The corresponding transmittance spectra are calculated at different strip length L_1 as shown in Fig. 4.15. The resonant frequency is red shifted from 2.81 THz to 2.87 THz as the strip length increases from 10 μm to 16 μm , which is due to the increase in the free electrons oscillation path and longer resonant period. The red shift can also be explained by interpreting the strip as an inductor in the LC circuit model. The inductance of the metamolecule is larger when the strips are longer, and the resonant frequency is lower. In addition, the Q factor of the resonance decreases for a longer strip length. The Q factor is defined as

$$Q = \frac{f_r}{\Delta f} \quad (4.7)$$

Fig. 4.15 Transitivity of the single- x -strip metamaterial with different strip length.

where f_r is the resonant frequency and Δf is the half-power bandwidth. The Q factor is an indication of the energy stored in the resonator for a certain input energy. The change in the Q factor of the resonant dip is due to the radiative loss on the metallic strip, which can be interpreted by calculating the induced magnetic field and surface current on the metamolecules. Fig. 4.16 shows the calculated results of the strip with length of (a) 10 μm and (b) 16 μm . The surface current average density is about the same on the two metamolecules. However, the longer strip has longer oscillation path and suffers more energy loss, and have a lower Q actor compared to the shorter strip.

Fig. 4.16 Induced magnetic field intensity and surface current on the single-x-strip metamaterial at different strip length of (a) 10 μm at 2.81 THz and (b) 16 μm at 2.87 THz.

(a)

(b)

Fig. 4.17 Transmittivity of single-x-strip and the double-x-strip metamaterial: (a) Double-x-strip and (b) transmittivity spectra under x -polarized incidence.

The element structure of a single-x-strip metamolecule is difficult to reconfigure. The metamolecule is modified by including two identical strips as shown in Fig. 4.17(a) and the reconfiguration can be easily realized by changing the gaps between the two strips. The metamolecule is named double-x-strip metamolecule and the gap between the

two strips is noted as g_0 . The transmittance spectra of the single-x-strip metamaterial and the double-x-strip metamaterial when $g_0 = 1 \mu\text{m}$ are numerically compared as shown in Fig. 4.17(b). The resonant dip of the two metamaterials are both at 2.86 THz. Therefore, the resonant dip frequency changes little when the gap g_0 of the double-x-strip metamaterial is small and does not change in this frequency regime.

Fig. 4.18 Transitivity of the double-x-strip metamaterial with different strip gaps.

The transmittance spectra of the double-x-strip metamaterial at different strip gap are numerically calculated as shown in Fig. 4.18. The resonant dip is blue shifted from 2.84 THz to 2.88 THz when the gap between the two strips is increased. The resonant frequency increase is due to the decrease of the effective capacitance between the two metal strips when the gap is getting larger. Meanwhile, the resonant strength decreases as g_0 increases from $1 \mu\text{m}$ to $7 \mu\text{m}$ and finally vanishes when $g_0 = 10 \mu\text{m}$. The suppression on the resonance strength is due to the capacitive coupling change between the two x-strips, which can be analyzed by investigating the oscillating surface current on the strips.

Figure 4.19(a) shows the surface current when the gap is $1\ \mu\text{m}$ at $2.85\ \text{THz}$, which corresponds to a large transmittance dip. Fig. 4.19(b) illustrates surface current when the gap is $10\ \mu\text{m}$ at $2.9\ \text{THz}$ where the resonance is suppressed. Compare the Figs. 4.19(a) and (b), the surface current has a much longer oscillating length when $g_0 = 1\ \mu\text{m}$ than that when $g_0 = 10\ \mu\text{m}$, which is due to the different capacitive coupling between the two strips. The shorter oscillating length corresponds to a higher Q factor. As a result, the metamolecule exhibits lower loss and the resonant dip is suppressed when g_0 is increased.

Fig. 4.19 Induced magnetic field intensity on the double-x-strip metamaterial at different strip gaps: (a) $1\ \mu\text{m}$ at $2.84\ \text{THz}$ and (b) $10\ \mu\text{m}$ at $2.88\ \text{THz}$.

It is noted that the distance between neighboring strips in adjacent metamolecules is also $10.5\ \mu\text{m}$ when g_0 is $10.5\ \mu\text{m}$. When g_0 is increased further, the metamolecule is

reconstructed with half of the original metamolecule and half of the adjacent metamolecule. As a result, the structure, and transmittivity spectra correspondingly, are the same when g_0 are $1\ \mu\text{m}$ and $20\ \mu\text{m}$, $4\ \mu\text{m}$ and $17\ \mu\text{m}$, $7\ \mu\text{m}$ and $14\ \mu\text{m}$, $10\ \mu\text{m}$ and $11\ \mu\text{m}$.

Fig. 4.20 Transmittivity of x-y-x-strip metamaterial: (a) schematic of the metamolecule and (b) the transmittivity spectra at different slab gaps.

Fig. 4.21 Induced magnetic field intensity and the surface current on the x-y-x-strip metamaterial at different strip gaps of (a) 1 μm and (b) 4 μm at 2.87 THz.

The coupling between in the double-x-strip metamaterial is changed when one of the strip oriented in the y -direction is inserted in between as shown in Fig. 4.20(a). This metamolecule is named as x-y-x-strip metamaterial and the corresponding strips are named as the left-strip, the center-strip and the right-strip. The center-strip has a length of 18 μm and width of 6 μm . The gap between the x -oriented strip and the center strip is g_1 . The transmittivity spectra of the metamaterial are calculated for different g_1 as shown in Fig. 4.20(b). A resonant dip is induced at 2.87 THz at a small g_1 of 1 μm . The resonant

strength is effectively suppressed and vanishes when g_1 is 4 μm . On the other hand, the frequency is not shifted as what occurs in the double-x-strip metamaterial.

The induced surface currents on the x-y-x strip metamaterial are numerically calculated at 2.88 THz in Figs. 4.21(a) and (b) for two different gaps 1 μm and 4 μm , respectively. Comparing the double-x-strip and x-y-x-strip metamolecules, the strong surface current is decreased in the x-y-x-strip metamolecule, which is due to the interaction between the x-strip and the y-strip. In addition, strong current is induced on the y-strip which flows along the x-direction when g_1 is 1 μm . As previously discussed, the strong surface current on the y-strip cannot be directly induced by the incident electric field, therefore, the surface current here is due to the capacitive coupling to the x-oriented strips. On the other hand, almost trivial surface current is induced on the y-strip when g_1 is 4 μm . Therefore, the loss is reduced and the resonant dip is suppressed.

The tuning of the electric response is studied by shifting the left-strip by a distance Δs . Initially, both g_1 are 4 μm which corresponding to a Δs of 0. The transmitted spectra of the metamaterial when Δs changes from 0 μm to 4 μm are shown in Fig. 4.22 (a) with x-polarized incidence.. As shown previously, there is no resonance when Δs is 0. As Δs increases, a resonant dip is induced slowly. A strong resonant dip is induced at 2.87 THz when Δs is 4 μm and at this state the left-strip is getting closed and contacted with the center-strip. In addition, another resonant dip at 2.97 THz is induced with a transmittivity below 0.1 and the Q factor of the dip is also smaller than that of the dip at 2.88 THz. The transmitted spectra of the x-y-x strip metamaterial under y-polarization are calculated in Fig. 4.22(b). A resonant dip at 2.91 THz is induced but is not much affected when the gap is increasing due to the resonance on the center-strip.

(a)

(b)

Fig. 4.22 Transitivity the x-y-x-strip metamaterial with different left-strip displacement under (a) x-polarized incidence and (b) y-polarized incidence.

Fig. 4.23 Induced magnetic field and surface current on the x-y-x-strip metamaterial when left-strip contacts with center-strip at (a) 2.88 THz and (b) 2.97 THz.

The induced surface current is calculated at 2.88 THz and 2.97 THz when $\Delta s = 4 \mu\text{m}$ as shown in Figs. 4.23 (a) and (b), respectively. The left-strip is contacted with the center-strip, and then conductive coupling is induced. The surface current at 2.88 THz is strong on all the strips and flows along the x -direction, which is similar to the cases as shown in Fig. 4.21(a). On the other hand, the current density at 2.97 THz is much stronger on the left-strip and the contacted part between the left-strip and the center-strip, and is trivial on the right-strip. Therefore, the transmission due the change of electric response is effectively tuned.

4.2.3 Fabrication Processes

The fabrication for the reconfigurable x-y-x-strip metamaterial is through silicon deep etching processes as described in Chapter 3. The strips are fabricated by patterning the 500-nm-thick aluminum layer on the substrate through optical lithography processes. The right-strip is isolated with the other two strips by etching the gap between them through DRIE process. The BOX layer under the right strip is then released from the substrate, making the right strip movable. In the initial state without electric bias on the micromachined actuator, the gap between the left-strip and the center-strip, and the gap between the right-strip and the center-strip are both 4 μm . The left strip is moved to the right side and contacted with the center strip with a displacement of 4 μm with electric bias of 10 V.

(a)

(b)

(c)

Fig. 4.24 SEM graph of the conductive coupling switchable metamaterial: (a) metamaterial and connected beam; (b) the top and (c) the perspective view.

4.2.4 Experimental Results and Discussions

The transmission spectra of the x-y-x-strip metamaterial are measured using FTIR in different tuning states. The experimental setup of the transmission measurement is illustrated in Fig. 4.25. The linear polarizers are used to test both the x -polarized and y -polarized transmittivity.

Fig. 4.25 Experimental setup for the transmission measurement.

Three states of the tunable metamaterial are measured when the left-strip shifting distance Δs is $0\ \mu\text{m}$, $3\ \mu\text{m}$ and $4\ \mu\text{m}$ and the experimental results are shown in Fig. 4.26(a) for x -polarization incidence and Fig. 4.26(b) for y -polarized incidence. In the frequency regime between 2.8 THz and 3.2 THz, no resonance other than the FP resonance is observed under x -polarized incidence, while a strong resonant dip is induced under y -polarized incidence at 3.02 THz. The FP resonance is due to the substrate effect and is a periodic Gauss-envelope with period of 0.4 THz. This dip is due to the energy loss from the center strip which is a radiative resonator under y -polarization. Comparing with the simulation results, the dip frequency under y -polarization is blue shifted by 0.1 THz,

(a)

(b)

Fig. 4.26 Comparison of measured (left column) and simulated (right column) transmittivity the x-y-x-strip metamaterial with different left-strip displacement under (a) x -polarized incidence and (b) y -polarized incidence.

which is mainly due to the deviation in geometric size between the fabricated sample and the simulated structure.

When the left-strip is moved to the right side with a displacement $\Delta s = 2 \text{ }\mu\text{m}$, there is still no resonance observed under x -polarization, which, however, is induced in the simulation results. This is because the resonance here is not strong enough as shown in the red line in Fig. 4.22(a), which cannot be detected in the experiment. When Δs is increased to $4 \text{ }\mu\text{m}$, in which state the left-strip is contacted with the center strip, two significant resonances at 2.93 THz and 3.13 THz are observed. This is agreed with the simulation results. As a result, a strong optical switching function can be realized through the reconfigurable metamaterial.

4.3 Summary

This chapter focuses on the study of the excitation and manipulation of the electric resonance in reconfigurable metamaterials and two metamolecules are designed to study different coupling mechanisms for the electric response control. In the first design, the electric response of the metamaterial is tuned by controlling the destructive couplings between a radiative resonator and a non-radiative resonator in real time. The induced optical response is similar to the EIT effect in quantum mechanics. The coupling is changed at different resonator positions and is realized through a micromachined actuator. The reflection spectrum is tailored by suppressing a strong resonant peak in the strong coupling state to no resonance in the weak coupling state. The second design controls the radiative loss of the metamaterial by manipulating capacitive couplings and conductive couplings between the resonators. The capacitive coupling is changed by tuning the distance between the resonators while the conductive coupling is induced by getting two resonators contacted. The electric resonant dip is then induced and suppressed at different coupling states.

The novelties of the study on the electric response in a reconfigurable metamaterial are summarized as follows:

- a) A real time control on the metamaterial electric response in THz wave is demonstrated through the metamolecule reconfiguration. Compared to other tuning methods, the structure reconfiguration has much flexibility in tuning the resonant frequency and strength through simple micromachined control.
- b) The work demonstrates that capacitive coupling and conductive coupling in the metamolecule play an important role in electric response. The coupling

mechanisms are investigated numerically and analytically, and provide a good understanding on the way to control metamaterial electric response.

CHAPTER 5

OPTICAL ACTIVITY TUNABLE METAMATERIALS

This chapter presents the design, fabrication and experiment of an optical active metamaterial for realization and manipulation. Two different metamaterial designs are presented including a planar chiral metamaterial and a semi-3D chiral metamaterial. The optical activity of the two metamaterial designs are numerically calculated. The planar chiral metamaterial is demonstrated with an extrinsic chirality which depends largely on the direction of incident wave. The optical activity is effectively tuned and the polarization rotation is switched between the states of clockwise and the anti-clockwise rotations. The semi-3D chiral metamaterial is fabricated by using silicon wet etching processing. Within a single layer stereo structure, it demonstrates intrinsic chirality and significant optical activity.

5.1 Planar Tunable Chiral Metamaterials

In this section a planar tunable chiral metamaterial is designed, fabricated and tested. A planar chiral structure is a planar structure which does not superimpose with its image unless it is lifted out from the plane. Strong optical activity can be obtained through the planar chiral metamaterial in transmitted EM wave with a proper incident direction.

5.1.1 Theory on Optical Activity

The optical activity, as discussed in Chapter 2, is inextricably linked to the chirality of the molecule structure or the molecule arrangement and usually referred in terms of two aspects: the circular birefringence and the circular dichroism. The circular birefringence presents the difference between the refractive indexes of the right circularly and left circularly polarized wave, which is characterized by the corresponding transmitted phase difference. On the other hand, the circular dichroism is the absorptivity difference between the right circularly and left circularly polarized wave and is proportional to the transmittance difference of the two polarized wave.

As discussed in Chapter 2, the circular birefringence and the circular dichroism can be interpreted as the transmitted polarization rotation angle θ and ellipticity angle χ , as illustrated in Fig. 5.1 when a linearly polarized wave passes through the material. θ and χ are related to the circular transmittance t_{++} and t_{--} , which are expressed as

$$\theta = (\varphi_{++} - \varphi_{--}) / 2 \quad (5.1)$$

and

$$\tan \chi = (t_{++} - t_{--}) / (t_{++} + t_{--}) \quad (5.2)$$

where t_{++} and t_{--} are the transmittivity while φ_{++} and φ_{--} are the transmittance phase shift of the right circularly and left circularly polarized wave, respectively.

Fig. 5.1 Polarization azimuth angle rotated by θ with an ellipticity angle χ when a linearly x-polarized wave propagates through an optically active material.

5.1.2 Planar Tunable Chiral Metamaterial Design

The design of the planar tunable chiral metamaterial is illustrated in Fig. 5.2. The concept of planar in the metamaterial is defined by assuming that the pattern on the substrate is thin enough and can be considered as zero thickness. In addition, the contribution of the substrate to the dimension is not considered either unless specified. The metamolecule of the planar metamaterial consists of metal strips along both the x -direction and the y -direction, which are noted as x -strip and y -strip, respectively. The strips are arranged such that the right side of an x -strip is facing to the top of a y -strip, while the left side of the x -strip is facing to the bottom of another y -strip as shown in Fig. 5.2(a). Such structure looks like a “downward staircase” when it is viewed from the left to the right. Although the planar structure does not possess intrinsic chirality, the extrinsic chirality can be raised under oblique incidence.

Fig. 5.2 Schematic of the planar chiral metamaterial in (a) the initial state, (b) the middle state and (c) the final state under oblique incidence.

The y-strip is designed to be shifted driven by a micromachined actuator along y -axis. The initial state of the metamaterial is defined when there is no y-strip shift. The metamolecule becomes like a thwart “T” structure when all y-strips are shifted up along the y -direction or a displacement of $(L_y - w)/2$ as shown in Fig. 5.2(b), where L_y is the length of the y-strip and w is the width of the strips. The metamaterial becomes a symmetrical structure with xz plane as the symmetric plane and is defined as the middle state of the metamaterial. The k vector is in the symmetric plane in this state making the metamaterial an achiral structure. The metamaterial is reconfigured to a planar chiral structure as the y-strip is further shifted with a total displacement of $L_y - w$ as illustrated in Fig. 5.2(c). Now it becomes staircase going upward and is defined as the final state of the metamaterial. To ensure the change in the pattern going from downward to going upward, the lattice constant of the metamaterial in y -direction, a_y , is set to be twice the length of the total displacement $L_y - w$. The geometries of the planar chiral metamaterial are list in Table 5.1, where a_x is the lattice constant in the x direction, L_x is the length of the x-strip and g is the gap between the x-strip and the y-strip.

Table 5.1 Geometric size of the planar chiral metamaterial

Geometric Size	Values (μm)
a_x	80
a_y	50
L_x	30
L_y	31
w	6
g	2

5.1.3 Simulation Results and Discussions

The transmission of the planar chiral metamaterial under normal and oblique incidence are investigated to characterize the optical response of the metamaterial. The linearly and circularly polarized transmissions are derived and calculated for the polarization rotation and circular birefringence of the metamaterial in THz wave regime.

5.1.3.1 Polarization Conversion under Normal Incidence

The normal incidence of the linearly polarized THz wave on the planar chiral metamaterial is first investigated. Only electric response is induced as the incident magnetic field is parallel to the metamaterial surface. The transmittance spectra of t_{yx} and t_{xy} at different y-strip shifting distance Δs are calculated from 1.2 THz to 2.4 THz shown in Figs. 5.3(a) and (b), respectively, where t_{ji} is the electric field ratio of the j -polarized transmitted wave to the i -polarized incident wave, which is the polarization conversion induced from the electric coupling between the x-strip and the y-strip. The simulation results show that the t_{yx} and t_{xy} are identical in the same tuning state. This is because the coupling factor between the two strips is the same. In the initial state when $\Delta s = 0$, t_{ji} is non-zero and is as high as 0.4 at 1.9 THz. t_{ji} across the whole spectrum investigated decreases to zero when the metamaterial is tuned from the initial state to the middle state when $\Delta s = 12.5 \mu\text{m}$, and then becomes non-zero again when the metamaterial tuning is moved from the middle state to the final state when $\Delta s = 25 \mu\text{m}$. The t_{ji} is the same for Δs_0 and the shifting $(25 \mu\text{m} - \Delta s_0)$. This is because the two states are the mirror image of

(a)

(b)

Fig. 5.3 Cross polarized transmittivity spectra of the planar chiral metamaterial at different tuned states with incidence in (a) x -polarization and (b) y -polarization.

each other and the couplings amplitude between the x-strip and the y-strip are the same. The phases of cross-polarized transmission, θ_{yx} and θ_{xy} in the initial state and the final state are calculated as shown in Fig. 5.4. $\theta_{yx} = \theta_{xy}$ at the same state have the same value. On the other hand, θ_{yx} at the initial state and at the final state differs by 180° . The same is true for θ_{xy} .

Fig. 5.4 Cross polarized transmitted phase shift of the planar chiral metamaterial in the initial state (blue line) and the final state (red line).

The origin of polarization conversion can be explained by investigating the induced magnetic field and the surface current on the metamaterial as shown in Fig. 5.5. In the initial state under x-polarization, the surface current on the x-strip is directly induced by the incident electric field and is denoted by the black arrows in Fig. 5.5.

Fig. 5.5 Induced magnetic field and surface current in the initial state, middle state and final state when under the x-polarization and y-polarization.

Opposite electric charges are thus induced on the two ends of the y-strips and oscillation current is formed and is denoted with red arrows in Fig. 5.5. In the middle state under x-polarization, the surface current is mainly concentrating on the x-strip with little current on the y-strip. Therefore, the conversion of scattered energy from x-polarization to y-polarization is almost zero in the middle state. In the final state under x-polarization, the surface current excitation and coupling are the same with that in the initial state, except

that the coupling induced current on the y-strip flows in opposite direction compared to that in the initial state. Therefore, there is a 180° difference between the θ_{yx} in initial state and the final state. The coupling under y-polarized incidence is the same as that in the x-polarization incidence, except that the current on the y-strip is directly induced while the current on the x-strip is excited due to the coupling between the strips. The optical activity of the normally incident planar chiral metamaterial, which can be derived from the transmittance under the circular transmittance, is discussed and compared with the obliquely incident case in the next section.

5.1.3.2 Simulation Results and Discussions under Oblique Incidence

The transmittance of the planar chiral metamaterial under both the right and the left circularly polarized EM wave, $\tilde{t}_{++}$ and $\tilde{t}_{--}$, are numerically calculated from 1.6 THz to 2.1 THz. The $\tilde{t}_{++}$ and $\tilde{t}_{--}$ here include both amplitude and phase shift information of the transmittance. The amplitude and phase shift of the initial state metamaterial are shown in Figs 5.6 and 5.7, respectively when the incident angle α increases from 0° to 45° . The wave vector k coincides with the normal planar surface under the normal incidence, and the metamaterial has no magnetic response as the magnetic fields is parallel with the planar chiral structure. As a result, no electro-magnetic coupling can be induced and the corresponding optical activity is zero, which is confirmed by comparing the amplitude t_{++} and t_{--} , and the phase shift φ_{++} and φ_{--} when $\alpha = 0$. The two parameters are the same under the right and the left circularly polarized incident wave. Therefore, both the circular birefringence and circular dichroism are 0 and there is no

polarization rotation. A difference in the transmitted amplitude and phase shift of the right and the left circular polarized wave are both observed when α becomes non-zero, which are getting larger when α increases. Therefore, both circular birefringence and circular dichroism become non-zero and demonstrate an optical activity.

Fig. 5.6 The phase shift of the right circularly polarized wave (blue line) and the left circularly polarized wave (red line) under different incident angles.

The polarization rotation angle and the ellipticity angle are derived from the difference of the transmittance between the right and the left circularly polarized wave using the

Eqns. 5.1 and 5.2 as shown in Fig. 5.8. Both angles are zero when $\alpha = 0^\circ$ across the frequency band investigated, which confirms that there is no optical activity in the planar metamaterial under the normal incidence. As the incident angel increases, the absolute value ϕ and $\tan(\chi)$ become non-zero which indicates a polarization rotation and the

Fig. 5.7 The transmitted amplitude of the right circularly polarized wave (blue line) and left circularly polarized wave (red line) under different incident angle.

(a)

(b)

Fig. 5.8 Optical activity of the planar metamaterial in the initial state: (a) polarization rotate and (b) ellipticity.

circular birefringence. Here, $\tan(\chi)$ is calculated instead of χ for its calculation convenience. It is proportional to χ in its definitional domain. The polarization rotation θ is increased up to 13° at 1.82 THz when α increases to 45° , which is an anti-clockwise polarization rotation. In addition, a negative θ of -6° is derived at 2.03 THz, which corresponds to a clockwise polarization rotation. Therefore, the optical activity from the planar chiral metamaterial is highly dispersive.

The inducing of the optical activity can be interpreted as shown in Fig. 5.9. The incident electric field induces an electric dipole p on the metamolecule and emitted an electric field E_p . Meanwhile, a magnetic dipole m is also induced on the planar chiral structure due to the spiraling surface current, which is similar to that in a helix with several turns. The m is either parallel or antiparallel with the electric dipole p . Both oscillating dipoles reradiate EM waves with electric field E_p and E_m . The combination of the two reradiated fields is the total scattering field E_s , which is not parallel to the incident E_i due to the non-zero E_m . Therefore, the transmitted light with the field of “ $E_i + E_s$ ” is rotated related from the original E_i direction

Fig. 5.9 Scattering of the planar chiral metamaterial.

(a)

(b)

Fig. 5.10 Optical activity of the planar metamaterial when y-strips shift by $12.5 \mu\text{m}$:

(a) polarization rotate and (b) ellipticity.

When the y-strip is shifted along the y-direction by 12.5 μm , the planar metamaterial becomes a symmetrical structure with the k factor of the incident wave in the symmetric plane as shown in Fig. 5.2(b). Therefore, the metamaterial with the incident wave forms an achiral architectural and manifests no optical activity regardless of the value of incident angle as long as the k factor is in the metamaterial symmetric plane. This is confirmed by numerically calculating the polarization rotation angle and ellipticity at this state as shown in Figs. 5.10(a) and (b), which gives a zero value for both parameters across the frequency band under different incident angle α .

The optical activity modulation realized by shifting the y-strip for different displacements Δs when $\alpha = 45^\circ$ is calculated as shown in Figs. 5.10(a) and (b), respectively. The polarization rotation reaches the peak at 1.82 THz in the initial state is blue shifted when the incident angle is increased. Meanwhile, the rotation angle is decreased to 0° when Δs increases to 12.5 μm . A negative polarization rotation is then observed in the band between 1.80 THz and 1.90 THz. Comparing the polarization rotation angle in the displacement Δs_0 and $25 \mu\text{m} - \Delta s_0$ across the whole spectrum, they always have the same absolute value with opposite sign. Therefore, the polarization rotation is reversed by tuning the planar chiral metamolecule to its enantiomer structure.

(a)

(b)

Fig. 5.11 Optical activity of the planar metamaterial at different y-strip displacement under 45 °incident angle: (a) polarization rotate and (b) ellipticity.

5.1.4 Experimental Results and Discussions

5.1.4.1 Experimental Setup

A THz Time-domain spectroscopy (THz-TDS) is used to measure the optical activity of the planar chiral metamaterial. Advanced to the FTIR which only measures the THz spectral intensity, the THz-TDS measures both the spectral intensity and the spectral phase information, which are important to characterize the metamaterial optical activity. The functional difference between the two systems is due to their different measuring mechanisms. As discussed in Chapter 3, the FTIR uses a continuous white light source and the measured intensity is the interferogram with no phase information accessible. The THz-TDS, instead, directly measures the time dependent electric field of THz radiation as illustrated in Fig. 5.12. An ultrashort (10–100 fs) laser pulse is split so that both the terahertz generator and receiver are irradiated. The most common terahertz generator and receiver is a photoconducting antenna. A sub-picosecond terahertz pulse wave irradiates the sample and when it propagates, the electric field strength changes. Rather than measuring the light intensity in the frequency domain, the time domain of the electric field strength is measured. The measurement of terahertz waves in the frequency domain usually uses a delay line. Repetitive terahertz pulse waves are measured and converted into frequency domain spectrum by Fourier transformation. The conversion recovers both intensity and the phase information of the wave, which are both essential to derive the optical activity of the metamaterial. The THz-TDS system used here is a Teraview spectra 3000, which measures the EM wave from 0.06 THz to 3 THz with a spectra resolution of 0.0075 THz. The transmission module is used for the activity measurement.

Fig. 5.12 The THz-TDS set up for the optical activity measurement.

5.1.4.2 Experimental Results and Discussions

The planar chiral metamaterial is fabricated using DRIE processes as discussed in Chapter 3. The SEM graph of the fabricated planar chiral metamaterial without electric bias is as shown in Fig. 5.13(a). The zoomed in structures of the metamolecules are shown in Figs. 5.13(a), (b) and (c) for the initial state, the middle state and the final state, respectively. The characterization of the optical activity requires the measurement of the circularly polarized transmittance. However, the circular polarizer for the THz wave is usually not available. Although waveplates can be used to convert the linearly polarized wave into the circularly polarized wave, they usually only work for a monochromatic wavelength. Therefore, a linearly polarized transmittance of the THz is measured using the corresponding linear polarizers due to the lack of the circular polarizer, the linearly

polarized transmittance measured can be converted into the circular transmittance and expressed as

$$\begin{pmatrix} \tilde{t}_{++} & \tilde{t}_{+-} \\ \tilde{t}_{-+} & \tilde{t}_{--} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \tilde{t}_{xx} + \tilde{t}_{yy} + i(\tilde{t}_{xy} - \tilde{t}_{yx}) & \tilde{t}_{xx} - \tilde{t}_{yy} - i(\tilde{t}_{xy} + \tilde{t}_{yx}) \\ \tilde{t}_{xx} - \tilde{t}_{yy} + i(\tilde{t}_{xy} + \tilde{t}_{yx}) & \tilde{t}_{xx} + \tilde{t}_{yy} - i(\tilde{t}_{xy} - \tilde{t}_{yx}) \end{pmatrix}. \quad (5.3)$$

where the $\tilde{t}_{ij}$ is the complex number of transmittance including both amplitude and phase information.

(a)

(b)

(c)

(d)

Fig. 5.13 SEM graph of the planar chiral metamaterial: (a) the perspective view; (b) the initial state, (c) the middle state and (d) the final state.

(a)

(b)

Fig. 5.14 Experimental results on optical activity of the planar metamaterial at different y-strip displacement under incident angle of 45° : (a) polarization rotation and (b) ellipticity.

The derived polarization rotation and ellipticity of the planar chiral metamaterial are plotted in Figs. 5.14(a) and (b), respectively. A polarization rotation peak of 4° is observed at 1.79 THz. The peak frequency is 0.03 THz red shifted compared to the simulation results, which is mainly due to the geometric deviation between the sample and the simulated model. The polarization peak is decreased to 0 when Δs is shifted by $12.5\ \mu\text{m}$, in which the metamolecules become an achiral structure. The polarization azimuth plane is then reversed with a further shift of the y-strip, which reconfigures the metamolecule to its enantiomer structure. Finally, a polarization rotation of -6° is observed at 1.79 THz when the metamaterial is shifted to the final state.

5.2 Semi-3D Chiral Metamaterials

The planar chiral metamaterial reported in the last section manifests its chirality depending on the wave vector of the incident wave. It largely relies on the incident condition of the EM wave and thus the realization of the optical activity through such design is largely limited. On the other hand, the metamolecules of different structures have been proposed to realize the intrinsic chirality. These include a quasi-2D chiral structure, a 3D chiral structure and a multi-layered chiral structure. The quasi-2D chiral structure, which derives the chirality through the symmetric breaking effect by the substrate, manifests very weak optical activity. The 3D chiral structure and multi-layered chiral structure realize strong optical activity, however, through a complex metamolecule architecture and a complicated fabrication process.

Here, we design a semi-3D metamaterial which depress a planar chiral structure in its normal direction. The metamolecule becomes intrinsically chiral and derives strong optical activity even without considering the symmetric breaking contributed by the substrate. The metal pattern of the semi-3D metamaterial designed is a single layered structure and can be easily fabricated.

5.2.1 Semi-3D Chiral Metamaterial Design

The proposed metamolecule for the semi-3D metamaterial is a metallic gammadion pattern on a trenched substrate as shown in Fig. 5.15(a). The trench is in a square shape at the substrate surface and excavated into the surface with a slope, which forms an inversed trapezoid body. The gammadion shaped metamolecules are then deposited on the trenched substrate. The gammadion structure is concentric with the trench and the gammadion center is deflected into the trench to adhere with the sidewall and bottom plane of the trench. As a result, a stereo metamolecule is created.

Fig. 5.15 Schematic of the semi-3D chiral metamaterial: (a) perspective view; (b) stereo gammadion metamolecule and (c) planar gammadion metamolecule.

The semi-3D gammadion metamolecule is a chiral structure and does not superimpose with any of its mirror image as illustrated in Fig. 5.15(b) even without considering the substrate effect. Therefore, a strong optical activity could be derived from such structure. In contrast, a planar gammadion metamolecule is not a chiral structure if the symmetric breaking effect by the substrate is not considered as shown in Fig. 5.15(c). The proposed structure, although in a 3D configuration, is easily realizable through planar fabrication process. The gammadion metamolecule is designed to respond to the terahertz wave and its lattice constant is $300\text{ }\mu\text{m}$, side length of the trench top square is $170\text{ }\mu\text{m}$ and depths h is up to $50\text{ }\mu\text{m}$.

5.2.2 Simulation Results and Discussions

The circularly polarized transmittivity of the semi-3D gammadion metamaterial is numerically calculated. The right and the left circularly polarized transmittivity, t_{++} and t_{--} respectively, are compared at different h as shown in Fig. 5.16. No difference is observed between t_{++} and t_{--} when $h = 0$ across the investigated frequency range. It is worth pointing out that the planar gammadion on a substrate is indeed a chiral structure due to the symmetric breaking between the gammadion and the substrate. The enantiomer, or the mirror image of the planar chiral structure on a substrate, does not superimpose with the structure. However, the optical activity induced in such a design is usually quite weak and not observable. As h increases to 10 μm , 20 μm and 40 μm , t_{++} and t_{--} start to distinguish with each other at multi-frequency bands with a center frequency at 0.44 THz, 0.48THz and 0.55 THz, which indicates an optical activity in the semi-3D gammadion metamaterial.

The value of the polarization rotation angle θ and ellipticity $\tan \chi$ of the semi-3D chiral metamaterial are calculated as shown in Fig. 5.17 for different trench depths derived from the circularly transmittance using the Eqns.5.1 and 5.2. The absolute value of the polarization rotation, which is 0° at planar substrate surface ($h=0$), starts to increase as the trench depth increases. Observing the polarization rotation at 0.44 THz, θ increases to 21° when h is 10 μm and gets to nearly 90° when h is 20 μm and 40 μm . The same trend occurs at the frequency of 0.56 THz. This trench depth here is only about 1/13 of the corresponding wavelength at 0.56 THz, and even smaller than that of the wavelength at 0.44 THz. Therefore, the large polarization rotation is actually realized in a deep subwavelength propagation distance through the semi-3D gammadion

metamaterial. The ellipticity, correspondingly, also becomes non-zero when the trench depth increases, which however, is not proportional to the trench depth.

Fig. 5.16 Numerically calculated right and left circularly polarized transmittivity t_{++} (blue line) and t_{--} (red line) at different trench depth h .

(a)

(b)

Fig. 5.17 Numerically calculated (a) polarization rotation and (b) ellipticity of the semi-3D gammadion metamaterial at different trench depth.

(a)

(b)

Fig. 5.18 Numerically calculated (a) polarization rotation and (b) ellipticity of the semi-3D gammadion metamaterial at different beam length.

Theoretically, only the semi-3D metamolecules with chirality realizes strong optical activity. This is demonstrated by investigating the optical activity dependence on the arm length of the semi-3D gammadion structure. When $s = 0$, the metamolecule is a cross structure which is achiral. The polarization rotation and ellipticity spectra of the semi-3D metamaterial at different arm length s are calculated in Figs. 5.18(a) and (b), respectively. Both the polarization rotation and the ellipticity are 0 across the calculated spectrum. No optical activity is obtained through the folded cross structure, although it is in semi-3D architecture. The polarization rotation and ellipticity become non-zero when s is a non-zero value. The polarization azimuth plane starts to rotate for about 10° when the arm length increases to $25\ \mu\text{m}$ at $0.52\ \text{THz}$, which further rotates up to nearly 90° at $0.44\ \text{THz}$. Therefore, it is concluded that the intrinsic chirality of the designed structure requires both stereo deflection and the planar chirality of the corresponding planar pattern.

The size of the trench, which is decided by the side length of the square, does not change the chirality property of the semi-3D gammadion metamolecule. The polarization rotation angle and the ellipticity value of the metamolecule at different trench side length b are calculated as shown in Figs. 5.19(a) and (b). As b increases from $100\ \mu\text{m}$ to $140\ \mu\text{m}$, there is almost no change in the polarization rotation and the ellipticity. Therefore, the optical activity is not so dependent on the side length of the trench.

We numerically analyze the polarization azimuth plane rotation in the planar gammadion metamaterial, deflected cross metamaterial and deflected gammadion metamaterial as shown in Fig. 5.20. EM waves with linearly x -oriented polarization at

Fig. 5.19 Numerically calculated (a) polarization rotation and (b) ellipticity of the semi-3D gammadion metamaterial at different trench width

0.55 THz are incident on the front side of the metamaterials Fig. 5.20(a). The polarization of the transmitted waves are monitored at the backside of the metamaterials with a distance of 450 μm as shown in Fig. 5.20(b). The monitors are about one wavelength away from the metamaterials which is in the far field regime. The transmitted polarizations are still in the x -direction after the EM wave propagates through the metamaterial of planar gammadion metamolecule and the metamaterial of trenched cross metamolecule, which indicate that the polarization does not rotate in the two metamaterials. On the other hand, the polarization direction of the transmitted wave is rotated anti-clockwise about 40° when the wave propagates through the metamaterial with depressed gammadion metamolecules.

The amplitude of the electric field distribution inside the structure is calculated with the incident EM wave is polarized along the x -direction at the frequency $f = 0.56$ THz, which corresponds to a wavelength of 535 μm . Therefore, the trench depth h of 40 μm is less than one tenth of the working wavelength and this semi-3D metamaterial manipulates the incident wave within deep sub-wavelength distance. The x -oriented and y -oriented vector components of the electric field in the metamaterial are investigated independently. Figs 5.21(a) and (d) are the amplitude of the x -oriented and the y -oriented electric field in a planar metamaterial with the identical size parameters with the semi-3D gammadion metamaterial, except that the trench depth is 0. Figs. 5.21(b) and (e) are the amplitude of the x -oriented and the y -oriented electric field in a semi-3D cross metamaterial with the identical size parameters with the semi-3D gammadion metamaterial, except that arm length s is 0. Figures 5.21(c) and (f) show the amplitude of the x -oriented and the y -oriented electric field of the semi-3D gammadion show the

Fig. 5.20 (a) Incident electric fields propagate through (b) planar gammadion structure (left column), semi-3D cross structure (middle column) and semi-3D gammadion structure (right column) and (c) transmitted electric fields.

Fig. 5.21 Magnetic field distribution on (a, d) planar gammadion structure and (b, e) semi-3D cross structure and (c, f) semi-3D gammadion structure in (a, b, c) x-orientation and (d, e, f) y-orientation with x-polarization.

amplitude of the x -oriented and the y -oriented electric field of the semi-3D gammadion metamaterial. Comparing the electric amplitude at the bottom of the substrate, the y -oriented field is much weaker than the x -oriented field for the planar gammadion metamaterial and the semi-3D cross metamaterial, which indicates a trivial polarization conversion. On the other hand, the y -oriented field is comparable with the x -oriented

Fig. 5.22 Surface current on the semi-3D gammadion metamolecule at (a) 0.47 THz and (b) 0.56 THz. (c) The radiation of the deflected “Z” structure.

field for the semi-3D gammadion metamaterial, demonstrating a large polarization conversion in the four four-folded rotational symmetric structure. As a result, a strong optical activity can be concluded.

The origination of the optical chirality is investigated by comparing the surface current of on the semi-3D metamolecule at 0.47 THz and 0.56 THz as shown in Figs. 5.22(a) and (b), which correspond to a 0 ° and 75 ° polarization rotation when $h = 40 \mu\text{m}$. The surface current is calculated under linearly polarized incidence oriented in the x -axis and the red arrows indicate the direction of the instantaneous current flow. The deflection gammadion can be seen as a structure consisting of two orthogonal deflected “Z” configurations. For either “Z” component, the surface currents on the two arms and the center strip flow along the same routine at 0.47 THz, which is due to the electric field driving along the x -direction. No cross-coupling between the electric resonance and magnetic resonance is induced at this frequency, and hence the polarization rotation is 0. On the other hand, the surface currents on the two arms flow in a routine opposite to that along the center strip at 0.56 THz, which can be further interpreted as in Fig. 5.22(c). The incident electric field induces an electric dipole p on the metamolecule and emitted an electric field E_p . Meanwhile, a magnetic dipole m is also induced on the deflected “Z” structure due to the spiraling surface current, which is similar to that in a helix with only one turn. The m is either parallel or antiparallel with the electric dipole p . Both oscillating dipoles reradiate EM waves with electric field E_p and E_m . The combination of the two reradiated fields is the total scattering field E_s , which is not parallel to the incident E_i due to the non-zero E_m . Therefore, the transmitted light with the field of “ $E_i + E_s$ ” appears to be rotated from the original E_i .

5.2.3 Fabrication Processes

The micromachined metamaterials are fabricated on a single crystal silicon substrate using the wet etching process as shown in Fig. 5.23. The squared trench is first etched on the silicon substrate. Thermal SiO₂ is deposited and patterned as squares on the substrate, which opens the wet etching window for the trench etch into the silicon. The wet etching process uses potassium hydroxide (KOH) solution which etches the silicon substrate at an etching rate of 1 µm/min in the vertical direction. In contrast to the DRIE process described in Chapter 3, the wet etching process is an anisotropic etching, which etches the material both vertically and horizontally. In this fabrication process, an inversed trapezoid body is etched out with a taper angle of 54.7°, which is a constant value related to the atom lattice structure of the silicon. The top side length of the body D is 170 µm and the bottom side length d is expressed as

$$d = D - 2 \frac{h}{\tan 54.7^\circ} \quad (5.4)$$

where h is the trench depth and d is calculated as 156 µm, 141 µm and 99 µm with a corresponding h of 10 µm, 20 µm and 50 µm. The lift off process is applied to pattern the metallic gammadion structure: The photo resist (PR) SU8 is uniformly spray coated on the trenched surface with a thickness of 5 µm after 2-min Argon clean on the Si surface. The Argon clean is used to enhance the metal layer adhesion. Aluminum is then deposited on the substrate with a thickness of 0.5 µm after PR is exposed and developed. Lift off is then processed using acetone solution. In the meantime, ultrasonic power is applied to accelerate the process. Aluminum on the PR is therefore be removed to realize the folded gammadion structure.

Fig. 5.23 Process flow of the semi-3D metamaterial fabrication: (a) Si substrate; (b) SiO₂ deposition and patterning; (c) wet etched Si; (d) SiO₂ removed and PR spray coating; (e) PR lithography; (f) metal deposition and (g) metal lift off.

The single layered chiral metamaterial has a lattice constant P of 300 μm and metal slab width w of 24 μm . The arm length s (indicated in Fig. 5.15) increases from 0 to 50 μm and 100 μm . The SEM graph of the THz metamaterials is shown in Fig. 5.24(a), which consists of 66×66 unit cell array and is approximately 2 cm^2 in scale. Figs. 5.24(b) and (c) show a close-up view of the unit cell structure.

Fig. 5.24 SEM graph of the pseudo-planar metasurface: (a) Overview of the metamolecule array and (b) close-up view of a single stereo metamolecule with trench depth of 20 μm and (c) 50 μm .

5.2.4 Experimental Results and Discussions

The optical activity of the sample is characterized by the transmitted polarization rotation angle θ and ellipticity angle χ , which relates to t_{++} and t_{--} as in Eqns. (5.1) and (5.2). It is usually difficult to measure t_{++} and t_{--} due to the lack of corresponding polarizer. Instead, in the four-folded rotational symmetrical structure, the circular transmission can be expressed using two orthogonal linear polarized waves as

$$t_{\pm\pm} = t_{xx} \pm it_{yx} \quad (5.5)$$

where t_{xx} and t_{yx} can be easily measured by using linear polarizer. The transmission is measured using TeraView system for different trench depths h . The measured amplitude and phase of t_{xx} and t_{yx} are converted to t_{++} and t_{--} using the Eq. (5.5). Finally, the polarization rotation angle θ and the ellipticity χ are derived using Eqns. (5.1) and (5.2).

The metamaterials are experimentally characterized using TeraView Spectra 3000 in the spectrum between 0.4 THz and 0.6 THz. The terahertz source is linearly polarized in vertical direction which is noted as x -polarization. Dry air is supplied in the measuring chamber to dispel water in atmosphere, which has large absorption in terahertz regime. The transmittivity of the semi-3D gammadion metamaterial with trench depth of 0 μm , 10 μm , 20 μm and 50 μm is measured as shown in Fig. 5.25. The corresponding polarization rotation θ and ellipticity angle χ are derived in Fig. 5.26. There is no polarization rotation observed when h is 0 at 0.56 THz although it theoretically possesses chirality due to the symmetry-breaking induced by the substrate. The optical activity due to such effect is too weak to be measured.

Fig. 5.25 Measured right and left circularly polarized transmittivity t_{++} (blue line) and t_- (red line) when trench depth h is 0, 10 μm , 20 μm and 50 μm .

When the trench depth is increased, the deflected structure itself possesses the chirality even without considering its coupling with the substrate. The polarization rotation increases to 2.5° , 5° and 14° when h increases to $10\ \mu\text{m}$, $20\ \mu\text{m}$ and $50\ \mu\text{m}$, respectively as shown in Fig. 5.26(a). At the same time, the tangent value of the ellipticity angle χ also increases from 0 to 0.03 when h increases at 0.58 THz as shown in Fig. 5.26(b). The increase of the optical activity is due to the enhanced electro-magnetic coupling from the deflected structure. The observed rotation is huge when h is $50\ \mu\text{m}$, or with a height of less than 1/10 of the wavelength. In terms of a rotary power per sample thickness in wavelength unit, the semi-3D gammadion metamaterial rotates the polarization azimuth angle four orders more than that in a quartz crystalline, which is only $21.7^\circ/\text{mm}$ at wavelength of 589 nm. The rotation is also 20 times larger than that in a quasi-2D chiral metamaterial with 1° rotation in a sample of 1/6 wavelength thick, and comparable with the giant rotation in some bilayered structures with 28° rotation in a sample of 1/30 wavelength thick.

Besides, the optical activity can be tuned by simply changing the trench depth to achieve desired optical activity at arbitrary frequency span. The optical activity is also measured for the stereo gammadion structure different arm length s with fixed trench depth of $50\ \mu\text{m}$ as shown in Fig. 5.27. There is no optical activity when $s = 0$ because the metamolecule is an achiral structure. As s increases to $50\ \mu\text{m}$, the metamolecule becomes chiral and weak optical activity is induced. The polarization rotation θ is 5° at 0.58 THz at this moment and goes on increasing to 14° at 0.56 THz when s is increased to $100\ \mu\text{m}$. Therefore, the optical activity can also be controlled by changing the gammadion arm

length. In addition, a small shift of polarization rotation peak is observed due to the shift of the electrical resonant frequency which results from the changing arm length.

(a)

(b)

Fig. 5.26 Measured (a) polarization rotation angle and (b) ellipticity of the normally incident light with different trench depth h .

(a)

(b)

Fig. 5.27 Measured (a) polarization rotation angle and (b) ellipticity of the normally incident light with different gammadion arm length s

5.3 Summary

This chapter focuses on the study of the excitation and manipulation of optical activity in metamaterials. Two designs are proposed to derive the optical activity with different mechanisms. The first design exhibits extrinsic optical activity through planar chiral structured metamolecules, which is largely dependent on the incident angle. The optical activity is effectively controlled by reconfiguring the chiral structure to an achiral structure and tunes the polarization rotation from zero to tens of degrees. The reconfiguration also switches the metamolecule between two enantiomer states to reverse the optical activity. The second design presents a semi-3D chiral metamaterial which manifests strong optical activity through the intrinsic chirality. The intrinsic chirality is realized by collapsing a single layered planar chiral structure. In this design, the optical activity can be altered for different collapsed height. Compared to the previous work, the semi-3D metamaterial designed in this thesis realizes giant optical activity through simplified fabrication processes.

The novelties of the study on the optical activity control in a reconfigurable metamaterial are summarized as follows:

- a) Real time tuning on the optical activity through the reconfigurable metamaterial is demonstrated for the first time. A giant polarization rotation of 13° is realized in the planar chiral metamaterial, which is tuned smoothly to 0° by reconfiguring the metamaterial to achiral, and the rotation is reversed by further tuning it to its enantiomer structure.

- b) The first realization of a significant optical activity through a semi-3D chiral metamaterial is demonstrated in THz wave regime. The metamaterial, consisting of single metallic layer in stereo architecture, derives a giant polarization rotatory power four orders more than natural material. A simplified and CMOS compatible fabrication process for the semi-3D chiral metamaterial are developed.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

Reconfigurable metamaterials to actively control different electromagnetic responses such as the magnetic response, the electric response and the optical activity to the terahertz wave have been innovated. Theoretical studies, structure designs, numerical calculations, fabrication technology and experimental demonstrations are presented. Different metamolecule structures are designed based on the theoretical analysis and optimized through numerical calculation. Micromachined fabrication processes are developed for the reconfigurable metamaterials. The tunable responses are demonstrated experimentally. The reconfigurable metamaterials have high potential to actively control terahertz wave in tunable filter, optical switch and polarizers among others.

The main innovation of the work is the successful demonstration on the significant tunability of the metamaterial's optical responses. The tunability is realized through a MEMS based technology which has the advantage of low cost, high efficiency and good compatibility with the massive CMOS fabrication processes. The reconfigurable metamaterials not only present a high flexibility for practical applications, but also provide a dynamic approach for the investigation on the relation between the

couplings in the metamolecules and the optical responses. The active controls on the three optical responses above are summarized as follows.

- (i) A reconfigurable metamaterial is designed to actively control magnetic response to terahertz wave. The wave is obliquely incident on the planar metamaterial with magnetic field components passing through the surface plane. Magnetic response is induced at around 0.8 THz and induces an asymmetric current in the metamolecules. The structure size dependence of the magnetic response is numerically studied and theoretically investigated. A micromachined fabrication process is developed for the reconfigurable metamaterial which tunes the magnetic resonant strength in real time.
- (ii) The electric response of the metamaterial to the terahertz wave is tuned in two designs. The first design presents a metamaterial which manifests EIT-like behavior at about 2.2 THz frequency. The destructive coupling between the radiative and non-radiative resonators induces a narrow spectrum window of high reflection. The coupling effect is analyzed both theoretically and numerically. The coupling factor is controlled through the reconfiguration of the metamaterial, which actively manipulates the reflection intensity. The second design studies the capacitive couplings between radiative structures separated by different distances. The conductive coupling is switched on by getting two separated metallic structures contacted. Significant switching effect in the transmission spectrum at around 3.1 THz is observed.
- (iii) Metamaterials with tunable optical activity are designed. A planar metamaterial with extrinsic chirality is designed and giant optical activity is observed at about

1.8 THz under obliquely incident wave. The polarization rotation is reversed by switching the chiral metamolecule to its enantiomer structure. It is also demonstrated that the giant optical activity can be tuned to 0 by reconfiguring the chiral metamolecule to an achiral structure. A semi-3D metamaterial is also designed with intrinsic chirality. Compared to 3D metamaterials, this chiral metamaterial can be easily fabricated and exhibits giant optical activity. The semi-3D structure is realized by collapsing a planar chiral pattern. The optical activity can be changed with different collapsed heights.

6.2 Recommendations

The development of the reconfigurable metamaterial to actively control and manipulate EM wave can be further improved. Below are some for future work:

- a) The reconfiguration of the metamaterial is achieved through micromachined technology, which utilizes a MEMS based actuator. Despite the successful demonstrations of the electromagnetic response realized by the MEMS actuator, the tuning speed is limited in microseconds and hence hinders the potential of the reconfigurable metamaterials applications in that requires fast tuning speed. One possible solution is to scale down the reconfigured structures to nanometer size. Smaller actuators with higher mechanic resonant frequency and higher switching speed is desired for the tuning of the scaled down structure. In addition, thermal effect can also be considered for reconfiguring the nano-scaled

metamolecules by constructing the metamaterial with materials of different thermal expansion coefficient.

- b) Although the reconfigurable metamaterial has high flexibility in tuning the optical response, the accuracy of the reconfigured displacement by the micromachined actuator is limited in micrometer size. On the other hand, the metamolecule responding to infrared light or optical visible light is in the size of nanometers. The reconfiguration through the MEMS actuator is thus difficult. To realize the tunability in the IR or optical metamaterials, the excitation of nonlinear material as discussed in Chapter 2 is preferred.
- c) The magnetic response of the planar metamaterial demonstrated in Chapter 3 is still not strong enough even after the optimization and modification of the structure. One reason to this weak response is that magnetic flux propagating through the metamaterial surface is small in oblique incidence. One approach to enhance the magnetic response is to design a stand-up structure which can directly respond to magnetic field under normal incident condition. The metamolecule can still be reconfigured in such 3D structure.
- d) In the planar chiral metamaterial design, strong optical activity is successfully demonstrated. However, it is largely dependent on the incident angle due to its extrinsic chirality. This can be improved by designing a two-layered metamaterial with intrinsic chirality.
- e) The semi-3D metamaterial with intrinsic chirality exhibits strong optical activity. However, the optical activity can only be tuned by changing the collapsed height of the structure. Real time tuning is, however, restricted. This can be improved

by suspending the planar pattern on the trench instead of depositing it along the trench contour. The suspended structure can be bent under mechanical or electric forces to realize the real time tuning for the optical activity.

- f) The circular birefringence of the optical activity is realized through cross coupling between the electric field and the magnetic field. Therefore, the optical activity is usually limited in the resonant spectrum. A multi-band resonant chiral metamaterial can be designed to increase the operating band width.

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