Chapter 1
Introduction

Abstract Recently, vigorous researches have been performed in the area of metamaterials (MMs). One outstanding effect is perfect-absorption MMs or MM-based perfect absorbers, that is, blackbody MMs. MM absorber has been firstly proposed in 2008, which had advantage of small size and thin thickness compared with the conventional absorbers. Since then, a great number of optimized MM absorber have been proposed for different application areas. Obviously, the MM single-band high absorption is inapplicable in some areas. Therefore, the research on broadband or multi-band high-performance MM absorber is necessary. Electromagnetic (EM) waves are in various polarization states, and to enhance the absorption the MM absorber should be designed to absorb EM waves independently of the polarization. The MM absorbers to be more practical should have the capability to cover large angle of incidence of the EM wave. THz or high-frequency MMs have received much attention, since conventional and natural materials hardly response to THz EM waves. Thus far, though most MMs were fabricated on rigid substrates, there have been several studies on flexible MMs. To achieve the perfect absorption, the method utilizing electromagnetically-induced transparency has also been investigated. Recent researches on MM absorbers and radiators include design of MM-based lenses and antennas, fabrication and measurements of MM structures for antenna applications, design and measurements of MM absorbing materials and screens, industrial applications of MM absorbers and radiators, etc.

Nowadays, it is said that we are living in the world of information. This means that we should exchange a huge amount of information with each other. Therefore, technologies are required to fulfill the desire of human being. In the forefront of technology, it is always essential to develop material possessing improved or new and/or novel properties useful for practical applications. This kind of needs has resulted in vigorous researches in the area of metamaterials (MMs) [1]. The term 'metamaterial' is used by Walser in 2001 for the first time [2]. A sophisticated definition is given by DARPA (Defense Advanced Research Projects Agency), USA, as MMs are a new class of ordered composites that exhibit exceptional properties not readily observed in nature. These properties arise from qualitatively

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new response functions that (i) are not observed in the constituent materials and (ii) result from the inclusion of artificially-fabricated, extrinsic, low-dimensional inhomogeneities [3].

Recently, people like to use a simpler definition; MMs are artificial media structured on a size scale smaller than the wavelength of external stimuli [4]. A detailed discussion of terminology is given in [5].

During the past decade, materials artificially engineered, the so-called MMs, which possess unnatural electrodynamic properties and effects, such as negative refractive index [6], inverse Doppler effect [7], superlensing [8], and electromagnetic (EM)-wave cloaking [9], have attained great achievements in photonic researches [10–13]. Together with developments of nanotechnology, MMs have not only produced the fascinating effects in a wide range of EM wave, but also been gradually applied to epoch-making improvements of microwave and photonic devices by exploiting the advanced phenomena [14]. The manipulation of effective parameters in man-made media increases diversification in the application of MMs [15]. One outstanding effect is perfect-absorption (PA) MMs or MM-based perfect absorbers (MMPAs), that is, blackbody MMs, which are useful to enhance the efficiency in capturing solar energy [16] and applied to plasmonic sensor [17], bolometer [18], wireless power transfer [19] and perfect light absorber have been rapidly developed [20–22]. The resonance that is established between inductive and capacitive portions of the circuit allows energy to be stored and subsequently dissipated via Ohmic and dielectric losses. In reality, absorption in the dielectric is much larger than the Ohmic loss in the conductor. Therefore, magnetic resonance, which produces antiparallel currents, has been exploited to generate the dielectric loss significantly [16, 18, 23].

MM absorber has been firstly proposed by Landy et al., which had advantage of small size and thin thickness compared with the conventional absorbers [24, 25]. Since Landy et al.'s work, a great number of optimized MM absorber have been proposed for different application areas, such as thermal images [26, 27], solar cell [28], sensor [17] and so on, and the optimization includes multiband [29–34], broad band [20, 35], polarization-insensitive [33, 34, 36, 37] and controllable band [38–40]. Obviously, the MM single-band high absorption is inapplicable in some areas [33]. Therefore, the research on broadband or multi-band high-performance MM absorber is necessary. Nevertheless, it is not easy to combine multi-band MMPAs with high efficiency, since the sensitive perfect absorption conditions are easy to be broken [33]. They recently demonstrated multi-band [33] and broadband [41] by using several kinds of resonators, and even dual-bands by using only one kind of resonator [34]. Furthermore, Ding et al. already reported broadband MM absorbers with quadrangular frustum pyramids using multilayer process and milling method, which showed wide-band absorption in 8–14 GHz [41]. However, the achievement is still a significant issue in the MMPA researches. In spite of numerous studies, many issues remain to be explored, for example, to relax the working conditions and to increase the number of absorption peaks and the absorption bandwidth [42–54], as well as to switch the absorption properties [38, 40] from microwave to infrared (IR) frequencies. Polarization-independent

MM absorber with wide-band high absorption at both low and high frequencies simultaneously has never been reported [1].

Recently, the absorption using MMs has attracted attention due to their tunable and controllable effects originating from alternation of the coupling at the resonance frequency of EM wave [39]. By manipulating the polarization in the MM, the embedded diode has led to switchable absorption in the GHz region [40]. Control of the distance between coupling components allows us to obtain the tunable dual-band perfect absorbers based on extraordinary optical transmission and Fabry-Pérot cavity resonance [38]. The reshaping of MM elements using micromachined actuators to devise the switchable dual-band absorption at THz frequency has been successfully realized in other work [55]. Furthermore, by utilizing the advantages, controllable absorbers are being developed to promise wide applications in tunable filters, detectors [17, 18], and optical switches [56] in near future.

The interaction between incident EM wave and MMs can be due to multiple reactions [57] and near-field coupling [56] between patterned and continuous metal layers [25]. The usual lattice constant of aforementioned general MM absorbers is 1/3–1/5 of the wavelength of indent EM wave.

EM waves are in various polarization states, and to enhance the absorption the MM absorber should be designed to absorb EM waves independently of the polarization. The endeavor to realize this has been performed. They realized the polarization-independent dual-wide-band MMPAs by using cone-type multilayered structure. It should be noted that, in order to achieve the dual-wide-band absorber, they apply the concept of third magnetic resonance [34]. By comparing between simulation and measurement, the lower frequency band is in excellent coincidence, while the higher frequency one is in slight discrepancy. The low-frequency absorption band turned out to be induced by the fundamental magnetic resonance and the high-frequency one due to the third magnetic resonance, and the polarization independence is presented. They also suggested that the dual broadband is demonstrated even in the infrared and the visible ranges [58]. People can obtain the MM absorption more or less independent of polarization at this moment.

The MM absorbers to be more practical should have the capability to cover large angle of incidence of the EM wave. The endeavor to realize this has been performed. The essential properties, such as low losses [59] or symmetry [60], are pursued to be elucidated and applied. Recently, by taking the advantage of diversification of MM designs, the unit cell, whose shape is based on natural structures, comes to emerge in this field of research [61]. They investigated the dependence of absorption on a wide range of incident angle for both transverse-electric (TE) and transverse-magnetic (TM) polarization [62]. The measured absorption decreased from 99.7 to 88 % when θ increased from 10 to 40°. In addition, the absorption frequency was nearly unchanged according to θ. The slight reduction of absorption according to incident angle can be explained by the coupling between external magnetic field of the incident EM wave and MMPA. Similarly to TE polarization, the single-peak absorption of 98.7 % was obtained at 400 MHz for the normal incidence in case of TM polarization. We keep working to obtain the MM absorption for even larger angle of incidence.

THz or high-frequency MMs have received much attention, since conventional and natural materials hardly response to THz EM waves. THz MMs are beyond this limitation and can interact with THz waves by tailoring unit cells to typical periodicities of tens or hundreds of micrometers [63].

Thus far, though most THz MMs were fabricated on rigid substrates [64–68] (e.g., silicon, sapphire), there have been several studies on flexible THz MMs, which were generally prepared on flexible substrates [25, 69–74], such as polydimethylsiloxane (PDMS), polypropylene (PP), polyethylene terephthalate (PET), and polyethylene naphthalate (PEN). Apart from the advantages of flexible substrates (e.g., high transparency, lightweight, low cost, and portability), they provide more degrees of freedom to manipulate THz responses. Li et al. demonstrated a continuous tunability of resonant frequencies through stretching the PDMS-based MMs [70]. Han et al. fabricated the multilayered PEN MMs and increased the bandwidths of resonant responses by 4.2 times compared with those of single-layered samples [72]. It was noted that electric resonance of SRRs played predominant roles in most flexible microwave, THz, infrared, and visible MMs [75–78]. However, electric-magnetic coupling has not been intensively studied in flexible MMs, which was mostly investigated in rigid MMs.

The effects of bending strain on electric-magnetic coupling were investigated for flexible THz MMs, which were either asymmetric or symmetric. A well-defined plasmon-induced transparency was demonstrated in the asymmetric flexible THz MMs, which were insensitive to the bending strain. However, for the symmetric flexible THz MMs, the bending strain strongly influenced the coupling, giving rise to continuous variations in transmission at a frequency of 1.1 THz [63].

To achieve the perfect absorption, not only the aforementioned ways but the method utilizing electromagnetically-induced transparency (EIT) has been investigated recently. The EIT is a quantum optical phenomenon to make an absorptive medium transparent to a resonant probe field owing to a destructive quantum interference between two pathways induced by a coupling field [79]. Unlike the quantum interference in atomic systems, the coupled components based on different mechanisms can be applied to realize the analogy of EIT in linear classical systems [80]. Most of this plasmonic EIT-like effects at optical frequencies were realized by using the near-field couplings between bright and dark modes [81–85] or between bright and bright modes [86, 87]. A scheme for realizing plasmonic EIT-like effects at optical frequencies in a stacked MM, which consists of two silver rings, was proposed [88]. The two silver rings are excited strongly by an incident wave. Based on Fabry-Pérot resonance coupling between the two resonators, polarization-independent EIT-like effects appear at optical frequencies. Using a planar MM, which consists of two silver strips, they theoretically demonstrated the plasmonic EIT-like spectral response at optical frequencies [84]. The two silver strips serve as the bright modes, and are excited strongly by the incident wave. Based on the weak hybridization between the two bright modes, a highly-dispersive plasmonic EIT-like spectral response appeared in their scheme. Moreover, the group index is higher than that of another scheme which utilizes the strong coupling between the bright and dark modes. The principle for the MM absorption based on EIT will be discussed, and the advances are also mentioned. One of the superiorities of MMs is that the EIT effect can be mimicked in a much easier way by using MMs [89, 90]. A different approach to create a multi-band MMPA was proposed by exploiting the EIT effect [91]. Generally, there is single absorption peak when external EM field excites only one plasmonic resonance. The key idea was that dual-band absorption can be achieved by employing the near-field coupling between bright and dark plasmonic modes even though only one resonance can be directly excited by the EM field. An extended model inducing multi-band absorption is also provided by considering the interaction between dark meta-molecules. Recent researches on MM absorbers and radiators include design of MM-based lenses and antennas, fabrication and measurements of MM structures for antenna applications, design and measurements of MM absorbing materials and screens, industrial applications of MM absorbers and radiators, etc.

The organization of the book is as follows. The Chap. 2 serves as Theoretical Backgrounds to MMPAs and their components. In the Chap. 3, MMPAs operating in different frequency ranges, including MHz, GHz, infrared and optical ranges, are examined. In the Chap. 4, MMPAs, based on EIT has been elucidated. Broadband and tunable MMPAs, and polarization-independent and wide-incident-angle MMPAs are also described in Chaps. 5 and 6, respectively, both of which are important for the practical applications. Perspectives and future works are discussed in the Chap. 7 to end this book.

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