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Published in:
2022 Photonics & Electromagnetics Research Symposium (PIERS)

DOI (link to publication from Publisher):
10.1109/PIERS55526.2022.9792666

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Mei, P., Pedersen, G. F., Liu, Q., Lin, X. Q., & Zhang, S. (2022). An Overview of Metamaterial Absorbers and Their Applications on Antennas. In *2022 Photonics & Electromagnetics Research Symposium (PIERS)* (pp. 1053-1060). Article 9792666 IEEE (Institute of Electrical and Electronics Engineers). https://doi.org/10.1109/PIERS55526.2022.9792666

An Overview of Metamaterial Absorbers and Their Applications on Antennas

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Abstract— Metamaterial absorbers, composed of artificial unit cells, have been widely investigated in the past few decades due to their unique performance of low profile, low cost, lightweight, and customized absorption responses, etc. The principles of the metamaterial absorber to absorb incoming electromagnetic waves lie in the impedance matching between the metamaterial absorber and free space (120π). This paper reviews the developments of the metamaterial absorbers, from narrow to wide band, single- to dual-polarization, polarization-sensitive to polarization-insensitive, small- to wide-angle absorption. The topologies and solutions to achieve wideband, dual-polarized, polarization-insensitive, wide-angle absorption metamaterial absorbers are clarified and discussed from the antenna reciprocity and equivalent circuit viewpoints. One of the applications of metamaterial absorbers is to reduce the scattering effects of a metal object by coating the metamaterial absorbers on the metal object. With the appearance of the band-notched metamaterial absorber and hybrid architecture, metamaterial absorbers can be readily integrated and co-designed with antennas to improve antennas' performance. This paper also presents the applications of the metamaterial absorbers on antennas from topological analysis to practical implementations. Two topologies to achieve low scattering antennas are described in detail. One is utilizing the notch band of a band-notched metamaterial absorber as the metal ground for an antenna (planar patch antenna, dipole antenna, or monopole antenna); within the notch band, the antenna can radiate efficiently, while the band-notched metamaterial absorbers can absorb incoming electromagnetic waves to reduce the scattering effects significantly out of the notch band. The other is using hybrid architecture to design reflectarray antennas with gain filtering and low scattering effects by proposing a unit cell with simultaneous phase shift and electromagnetic wave absorption properties. The manipulations of the phase shift and electromagnetic wave absorption are independent of each other to facilitate the design of the reflectarray antennas. The future perspectives on metamaterial absorbers are discussed finally.

1. INTRODUCTION

Electromagnetic absorbers, by their names, are kinds of stuff capable of absorbing electromagnetic waves, which can be utilized to reduce the scattering properties of objects. The most familiar electromagnetic absorbers are pyramid-shaped absorbers loaded with carbon/ferrite lossy powder, which are necessary materials in the equipment of anechoic chambers. The pyramid shape can direct the incoming electromagnetic waves to the internal of the absorbers, where the electromagnetic waves will decay significantly during the propagation, thereby equivalently resulting in the electromagnetic wave absorption. However, the pyramid-shaped absorbers suffer from noticeably high profile and huge weight, especially at the low-frequency bands as the profile of the pyramid is usually inversely proportional to the operating frequency.

Metamaterial absorbers are kinds of artificially structured surfaces, composed of lots of periodical unit cells, featuring low profile, lightweight, and versatile absorption performance. As a result, metamaterial absorbers have undergone extensive investigations in the past few decades. The work principles of metamaterial absorbers mainly lie in the impedance match between the metamaterial absorbers and free space. The electromagnetic properties of metamaterial absorbers can be characterized by effective permittivity ($\varepsilon_0\varepsilon_{eff}$) and permeability ($\mu_0\mu_{eff}$). To match with free space, the impedance of the metamaterial absorber that is calculated with $Z = \sqrt{\varepsilon_0\varepsilon_{eff}/\mu_0\mu_{eff}}$ should be equal to that of free space that is $Z_0 = \sqrt{\varepsilon_0/\mu_0}$, resulting in $\varepsilon_{eff} = \mu_{eff}$ of the metamaterial absorbers. The effective permittivity and permeability of metamaterial absorbers are generally retrieved from their S-parameters by doing some calculations. As the metamaterial absorbers typically serve as one-port devices, we can simply check the input impedances and compare them with the impedance of free space (120π) instead of extracting the effective permittivity and permeability mathematically. On the other hand, the effective permittivity/permeability and input impedance of metamaterial absorbers are highly associated with the specific structure of the unit cell. Therefore, the investigations and studies on metamaterial absorbers are mainly focused on proposing and optimizing the structures of unit cells. Due to the low profile of metamaterial absorbers, it provides probabilities to integrate them with antennas to improve antennas' performance such as reducing their scattering properties.

This paper gives an overview of metamaterial absorbers and their applications on antennas. The developments of metamaterial absorbers are presented first, where the operating bands of metamaterial absorbers are extended from one band to multiple bands; the bandwidths are enhanced from narrow to wide band; the operating polarizations are developed from polarization-sensitive to polarization-insensitive; the absorption angles are broadened from small to wide angle, etc. The applications of metamaterial absorbers are described, mainly focusing on reducing the scattering property of a metal plate, the gain-filtering and low-scattering properties of antennas, and energy harvesting and wireless power transfer using metamaterial absorbers. Finally, the future developments on metamaterial absorbers are discussed.

2. METAMATERIAL ABSORBERS

2.1 Narrow and wide band metamaterial absorbers

In [1], Landy, *et al.* proposed a perfect metamaterial absorber using two metamaterial resonators that coupled separately to electric and magnetic fields, resulting in near-unity absorbance at a single frequency. Due to the resonant characteristics of the resonators, the bandwidth of the metamaterial absorber was typically narrow, which limits its practical applications. To this end, some technologies were developed to broaden the bandwidths of metamaterial absorbers. One of the effective solutions was to utilize a multilayer resonant-based unit cell [2], [3], where the resonant frequency of each layer was properly designed so that the operating frequencies of all layers can form a wide band. Usually, the more layers of the unit cell, the wider bandwidth the corresponding metamaterial absorber can achieve. Therefore, such metamaterial absorbers suffer from high profiles if wide bandwidth is preferred. Another solution to achieve wideband absorption is loading resistive components e.g., lumped resistors, resistive film, etc., where the introductions of the resistive components can modify the input impedance of the metamaterial absorber to make it match with free space well in a wide band if proper resistors are selected [4]-[7]. To analyze the wideband impedance matching between the metamaterial absorber and free space, the equivalent circuits of the metamaterial absorber were established for example in [4], where the metallic pattern of the unit cell is modeled with lumped inductors and capacitors, the supporting substrates, and free space are modeled with transmission lines with different propagation constants. The values of components in the equivalent circuit can be extracted and determined by referring to [8]. The input impedance (Z_{in}) of the metamaterial absorber can be formulated according to the equivalent circuit. As a result, the reflection coefficient of the metamaterial absorber is calculated with $\Gamma = (Z_{\text{in}} - Z_0) / (Zin + Z_0)$, where Z_0 is the characteristic impedance of free space. In [9], the authors proposed a methodology to design a wideband metamaterial absorber from an antenna reciprocity viewpoint. As is known to all, a passive antenna is a reciprocal device, which can receive and transmit electromagnetic waves with the same properties (bandwidth, radiation patterns, etc.). When a passive antenna serves as a receiving antenna, it can receive electromagnetic waves from free space. If the passive antenna is terminated with a lumped resistor, the received electromagnetic waves will be consumed by the lumped resistor so as to achieve the effect of absorption. This methodology converts the design of a wideband absorber into the design of a wideband antenna. In [9], the authors designed a wideband dipole antenna first, the corresponding wideband absorber was achieved by soldering a proper lumped resistor at the input port of the dipole antenna according to the input impedance of the dipole antenna. Using the antenna reciprocity, an absorber for large incidence angles was reported in [10] by selecting a monopole antenna as the unit cell. As the radiation pattern of a monopole antenna is usually a conical beam, there is a null at broadside direction, and the main beam points to the off-broadside direction, thereby enabling the corresponding absorber capable of absorbing electromagnetic waves from large incident angles.

2.2 Multiple bands metamaterial absorbers

Wideband metamaterial absorbers are capable of absorbing electromagnetic waves in a wide band, which are suitable for wideband applications. The metamaterial absorbers, however, are preferred to absorb electromagnetic waves at some specific different bands in some application scenarios. The effective method to achieve a multiband metamaterial absorber was utilizing multiple resonators, each of which was responsible for an absorption band [11]-[14]. Besides, the operating bands can be controlled by adjusting the dimension of each resonator. The bandwidths of such metamaterial absorbers are usually narrow due to the resonant properties of the resonators. The fractional bandwidths were only around 1.0% for the multi-band metamaterial absorbers reported in [11]-[13]. To broaden the bandwidth of each absorption band, the authors proposed a methodology to design a multiband absorber with wide absorption bandwidths using impedance matching theory [15]. In this methodology, the authors first designed a triple-band frequency selective surface (FSS) based on multilayer and multiple square-ring structures. The bandwidth of each passband can be adjusted by simply varying the dimensions of the multiple square rings. The reflection coefficient at one port of the FSS will be maintained when the other port is terminated with a matching load. As a result, the two-port FSS is converted into a one-port absorber. The matching load to terminate the FSS can be implemented by a wideband absorber described in the above subsection. The triple-band absorber with wide absorption bandwidths reported in [15] could result in fractional bandwidths of more than 5.0% that were much higher than those in [11]-[13].

2.3 Polarization-insensitive and wide-angle metamaterial absorbers

Compared to the single-polarized metamaterial absorbers, the polarization-insensitive metamaterial absorbers are more competitive as the polarization of the incoming electromagnetic wave is usually unknown. The polarization-insensitive properties of metamaterial absorbers are in high association with the specific structures of the unit cells. According to the polarization-insensitive metamaterial absorbers reported in [12]-[14], [16]-[19], it was found that the unit cells to comprise the metamaterial absorber are all highly symmetrical. Indeed, the highly symmetrical unit cells can result in the same frequency responses for the x- and y-polarized normal incidence waves. Any polarization of incoming electromagnetic waves can be decomposed into x- and y-polarized incidence waves. If the metamaterial absorber is capable of dual-polarization that the frequency responses on the two orthogonal polarizations are the same, it should be polarization-insensitive accordingly. Wide-angle metamaterial absorbers mean the metamaterial absorber can absorb the incoming electromagnetic waves from large oblique incidence angles. For resonant-based metamaterial absorbers with narrow bandwidths, they usually demonstrate the wide-angle absorptions as well [12]-[14], [16]-[19]. The absorption angles of such metamaterial absorbers can reach 70 degrees.

2.4 Band-notched metamaterial absorbers with high notch-band-edge selectivity

The above-mentioned metamaterial absorbers with narrow, wideband, multiband, polarization-insensitive, and wide-angle performance have been widely studied in the past years. Very recently, the authors proposed and implemented a band-notched absorber with high notch-band-edge selectivity [20]. The implementation of the band-notched absorber greatly highlights the advantages of metamaterial absorbers compared with the pyramid absorbers. The ideal frequency response of a band-notched absorber is depicted in Fig. 1, where the band-notched absorber demonstrates full reflectance from f_1 to f_2, while it can absorb incoming electromagnetic waves when the frequency is less than f_1 or higher than f_2. In [20], the authors presented detailed procedures to design a band-notched absorber with high notch-band-edge selectivity. It started with a wideband absorber, then properly introducing two reflection points within the absorption band. The two reflection points can form a flat notch band. By changing the frequencies of the two reflection points by adjusting certain dimensions, the frequencies and bandwidth of the notch band can be controlled. The equivalent circuit of the corresponding band-notched absorber was established to analyze and explain the generation of the notch band. Also, the equivalent circuit can give some guidelines to control the frequencies and bandwidth of the notch band. According to the results in [20], the authors developed a dual-polarized and band-notched absorber in [21]. The advent of the band-notched absorbers opens a new path to co-design with antennas to improve the antennas' performance, which will be elaborated on in the next section.

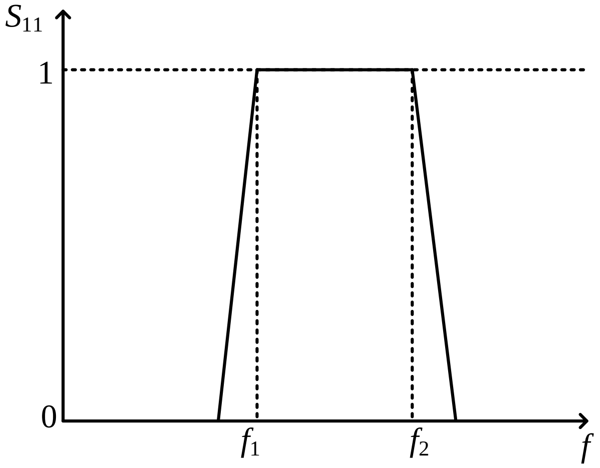
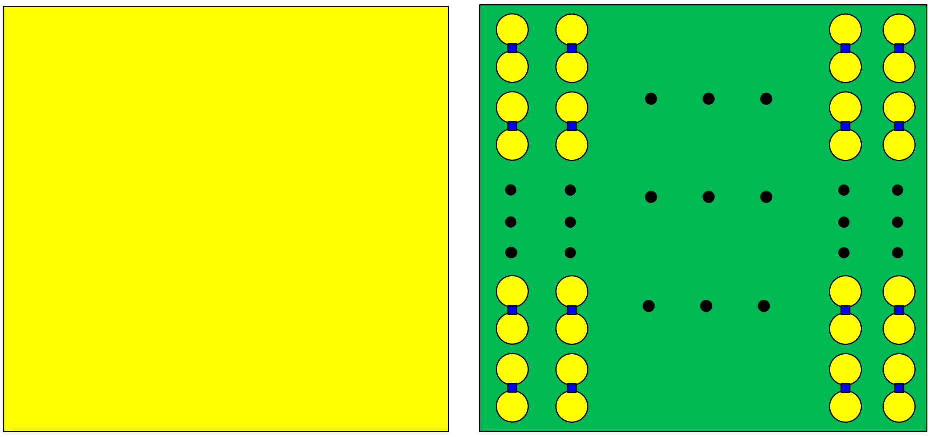


Fig.1. The ideal frequency response of a band-notched absorber.

3. APPLICATIONS OF METAMATERIAL ABSORBER ON ANTENNAS

This section describes the applications of metamaterial absorbers on antennas. As the metamaterial absorbers can absorber incoming electromagnetic waves, the most intuitive application of metamaterial absorbers is coating on a metal object to reduce the scattering performance of the metal object. Fig.2 gives simple diagrams of a pure metal plate and the same size metal plate coating with single-polarized wideband metamaterial absorbers enabled by loading resistors. The monostatic scattering performance of the pure metal plate loading with and without wideband absorbers are simulated and presented in Fig.3, where it is observed that the pure metal plate coating with wideband metamaterial absorbers can achieve significantly low scattering performance compared with that of a pure metal plate, verifying the effectiveness of the wideband metamaterial absorbers in reducing the scattering performance of a metal plate. The metamaterial absorbers can also coat in the curved metal surface to reduce its scattering performance if the metamaterial absorbers are fabricated with flexible substrates that can be conformal to the curved metal surface [22]-[25].



(a) (b)

Fig.2. (a). Pure metal plate. (b). the same size metal plate coating with wide metamaterial absorbers.

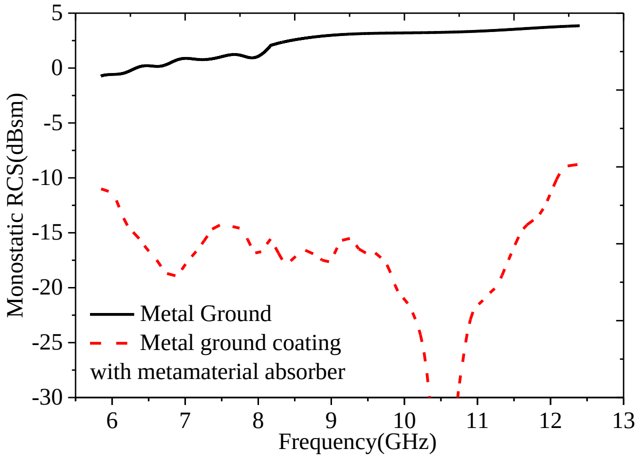


Fig. 3. The simulated monostatic scattering performance.

As seen in Fig.1, the band-notched absorber can offer a full reflectance which can be equivalently served as a metal ground for an antenna or a reflector. Within the notch band, the antenna can radiate properly, while the antenna can achieve low scattering performance out of the notch band. Some antennas co-designed with band-notched were reported in [26]-[31] to improve antennas' performance. The authors fully utilized the full reflectance of the band-notched absorber as metal grounds of dipole antenna [26] and monopole antenna [27]. Fig. 4 gives the frequency response of the band-notched absorber in [26], where it can offer full reflectance from 7.8 to 9.0 GHz, absorb electromagnetic waves from 4.5 to 7.8 GHz, and 9.8 to 14 GHz. Fig. 5 presents the configurations of the band-notched absorbers with a dipole antenna reproduced from [26]. The circular split ring resonator etched on the dipole-shaped metal patches in the upper layer and the rectangular metal array in the bottom layer contribute to the notch band. By adjusting the dimensions of the circular split-ring resonator and rectangular metal array, the bandwidth of the notch band can be controlled. The dimensions of the dipole antenna were properly selected to make it work within the frequencies of the notch band.

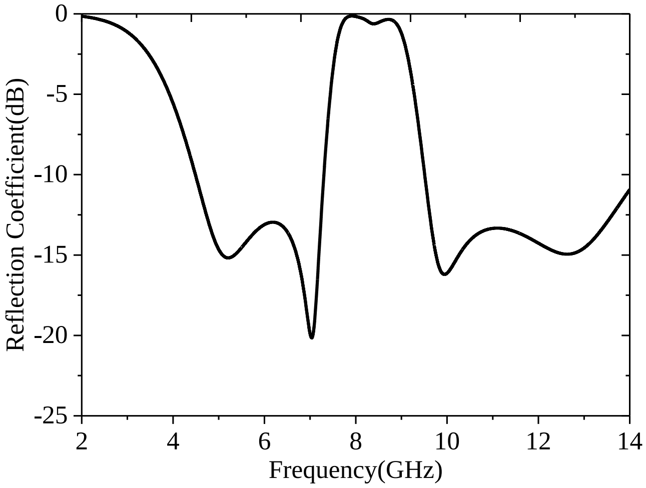


Fig. 4. The frequency response of the band-notched absorber in [26].

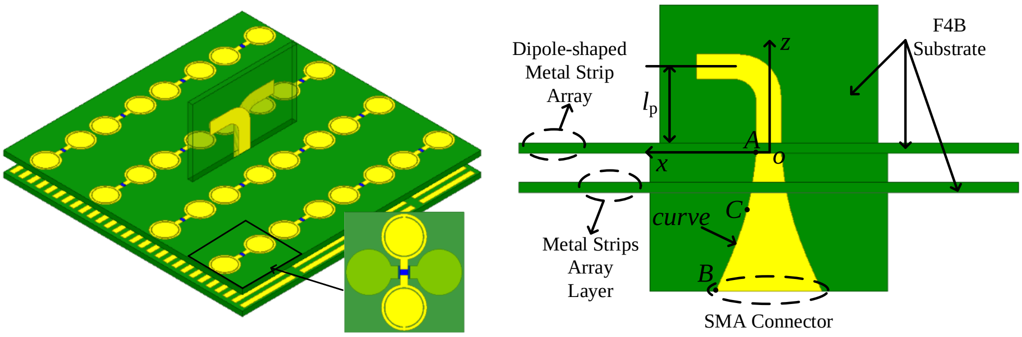
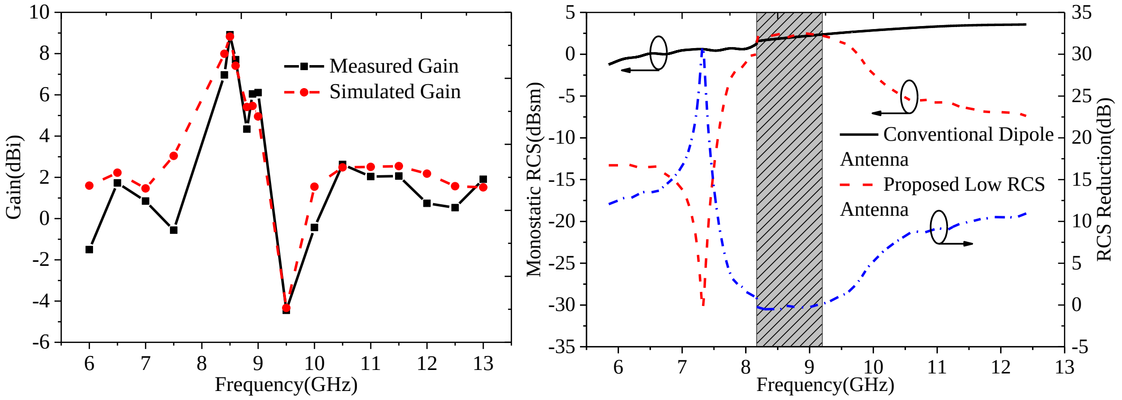


Fig. 5. The geometries of the band-notched absorbers with dipole antennas. (Reproduced from [26])



(a)

(b)

Fig.6. (a) Simulated and measured boresight gains of the proposed design. (b). Measured monostatic scattering properties of the proposed design and a referred antenna. (Reproduced from [26])

The realized gains of the proposed design with frequencies are measured and plotted in Fig. 6 (a), where the simulated results are also presented for comparison. Fig. 6 (b) gives the measured monostatic scattering properties of the proposed design and a referred antenna. The referred antenna is a dipole antenna with the same size metal ground as the proposed design. It is observed that the dipole antenna can properly radiate within the notch band, while it demonstrates significantly low scattering properties out of the notch band compared to the referred antenna.

Metamaterial absorbers can also be co-designed with antennas as radomes to reduce the scattering properties of antennas as reported in [28], [29]. In [28], the authors presented a low scattering and low-profile antenna using frequency selective metamaterial absorbers. The frequency selective metamaterial absorbers can offer a passband. A patch antenna was inserted into the bottom layer of a double-layer frequency selective metamaterial absorber, where the operating frequencies of the patch antenna coincide with the passband of the frequency selective metamaterial absorbers. Within the passband, the electromagnetic waves emanating from the patch antenna can propagate through the frequency selective metamaterial absorbers, then radiate to free space, while the frequency selective metamaterial absorbers can absorb the incoming electromagnetic waves out of the passband.

Another application of absorbers on antennas is to design low-scattering and gain filtering reflectarray antennas, which is much more challenging compared to applications of metamaterial absorbers on antennas reported in [26]-[29]. For a reflectarray antenna, the unit cell should offer phase shifts to compensate for the desired phase shifts due to the propagation path difference from the feed source to the unit cells. for a low-scattering reflectarray, the unit cells need to fulfill the simultaneous phase-shifting and electromagnetic wave absorption performance. In [31], the authors proposed a hybrid design concept involving the band-notched absorbers and dielectric lens, where the band-notched absorbers provided the full reflectance and electromagnetic wave absorption, and the dielectric lens was responsible for the phase shift. By properly designing the dielectric lens, it could be coated on the band-notched absorber directly to form a new unit cell. By adjusting the height of the dielectric lens, it can offer a reflection phase coverage of 360 degrees. The measured results in [31] demonstrated that the proposed reflectarray antenna featured gain-filtering. Within the notch band, the reflectarray antenna could radiate properly and achieve a focused beam at broadside direction, while the reflective panel of the reflectarray antenna absorbed the incoming electromagnetic waves out of the notch band, resulting in low gains equivalently. As a result, the gain-filtering property was formed. The measured scattering performance also implied that the proposed reflectarray antenna could offer significantly low scattering performance out of the notch band.

Using metamaterial absorbers for energy harvesting and wireless power transfer is a new application of metamaterial absorbers [32], [33]. As metamaterial absorbers can absorb electromagnetic waves from free space, the received electromagnetic waves can be converted into direct current by using rectifier circuits. The input impedance of the rectifier circuit should be conjugately matched to the metamaterial absorbers so that the received electromagnetic waves by the metamaterial absorbers can be converted into direct current efficiently.

4. CONCLUSION

This paper gives an overview of metamaterial absorbers and their applications on antennas. First, the developments of metamaterial absorbers are described in terms of the bandwidth, the number of the absorption band, polarization-insensitive absorption, wide-angle absorption, and notch band. The advent and implementation of band-notched metamaterial absorbers offer a new paradigm to co-design with antennas to improve the antennas' performance. The applications of metamaterial absorbers on antennas are presented then. The most intuitive application of metamaterial absorbers is coating on a metal object to reduce the scattering performance of the metal object. Fully using the notch band as the metal ground of an antenna, the antenna can radiate properly within the notch band, while it can demonstrate low- scattering performance out of the notch band. Besides, frequency selective metamaterial absorbers can serve as a radome for an antenna, where the antenna can be inserted into the frequency selective metamaterial absorbers. The antenna can radiate properly within the passband of the frequency selective metamaterial absorber, while it can also demonstrate low-scattering performance out of the passband. The band-notched absorber can also be properly combined with a dielectric lens to implement a low-scattering and gain-filtering reflectarray antenna, where the band-notched absorber is responsible for the full reflectance and electromagnetic wave absorption, and the dielectric lens offers desired phase shifts by simply changing the heights of the unit cells of the hybrid lens. As metamaterial absorbers can absorb electromagnetic waves in free space, the received electromagnetic waves can be properly converted into direct current by loading rectifier circuits on metamaterial absorbers for energy harvesting and wireless power transfer.

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