Metamaterial-Based Absorptive Structures

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Metamaterials are artificially-engineered synthetic materials having periodic arrangements of sub-wavelength metallic/dielectric structures or resonators. Metamaterials have demanded a lot of recognition, due to their exotic and unique attributes such as negative-refraction, microwave cloaking, absorption of the inverse Doppler effect, etc. After the investigation of the first 'perfect meta-absorber' proposed in 2008, metamaterial absorbers (MMAs) have drawn significant interest from the microwave and optics community. These MMAs have multifarious features compared with the conventional Salisbury absorbers, such as a low-profile and light weight. Moreover, they are thinner, more compact, and more efficient than conventional absorbers. They have many applications for wireless communication and other optical systems, including MIMO antenna isolation, EM interference reduction, stealth technology, and solar photovoltaics.

metamaterial silver-nanoparticle wearable tunable flexible absorber microwave

1. Introduction

In the literature, several investigations have been carried out in this exciting area of metamaterial absorbers (MMAs) from the microwave-visible spectrum [1][2][3][4][5][6][7]. Most of the reported work is based on rigid substrates without frequency spectrum reconfigurable abilities. The authors in [8] presented a multi-band metamaterial absorber fabricated on an FR4 substrate at the corresponding frequency points of 4.11, 7.91, 10.13, and 11.51 GHz. The metamaterial absorber reported in [9] contains wideband features having the operating range of 7–12.8 GHz, which is also developed on a rigid substrate. Similarly, different multi-band MMAs have been proposed in [1][10][11] which are also fabricated on rigid/solid substrates. Moreover, most of the present literature and investigations are based on the solid/rigid substrates [2][12][13] However, many applications required a flexible MMA with features such as the mitigation of multipath effects in a radome or the reducing of scattering noise in automotive radars. The authors in [14], going a step further, proposed a single-band tunable MMA ranging from 4.35 to 5.85 GHz. Such MMAs can have applications in software-defined radios. The authors in [15] presented single and dual-band absorbers at 77, 95, and 110 GHz on a flexible polyimide substrate. In [16], the authors proposed a dual-band flexible MMA with absorption peaks at 16.77 and 30.92 GHz.

Recent and modern communication systems and technological development in microwaves and optics require devices with multifarious features of miniaturization, cost-effectiveness, tuneability, and flexibility. To see contemporary advancement and evolution in the field of metasurfaces, a lot of research can be done to meet the modern standards of communication systems. Most of the recent meta-devices are fabricated on rigid and hard substrates, but the world is not flat and smooth: a lot of applications include curvilinear surfaces, conformal implementation, and wearable sensors [17], etc. where soft and flexible devices are needed [18]. Furthermore, modern communication systems demand efficient and multiband metasurfaces, to meet their future requirements. Therefore, the quest for flexible and tunable metasurfaces is inevitable.

2. Non-Flexible Absorbers

After the investigation of Landy's seminal work on perfect metamaterial absorbers [19], there has been huge interest in the different microwave and optics communities in the field of metamaterial absorbers. In Landy's initial work, they used a rigid/solid substrate of FR-4 to design the single and narrow-band absorbing device at 11.5 GHz. They also exploited and optimized the same unit cell to construct the metamaterial absorber for the terahertz band [20]. Thereafter, people started to explore metamaterial-based absorbers for dual-band, tri-band, multi-band, and wideband operation, targeting different operating spectrums including microwave, terahertz, visible and infrared [4][21][22][23]. Huang et al. investigated the tri-band perfect metamaterial absorber by designing three different sizes of square-shaped rings [24]. Afterward, Shen et al. also designed a tri-band perfect metamaterial absorber by using multiple resonators of different dimensions [25]. Furthermore, people started to study different techniques to implement multi-band and wideband metamaterial absorbers for different operating ranges. Usually, multi-layered- and multi-resonator-based configurations are used to enhance the bandwidth of the metamaterial-based absorber [12][25]. Shen and his co-workers arranged multiple layers in a vertical direction to enhance the absorption spectrum of metamaterial in the microwave regime [12]. A similar research group also designed the broadband metamaterial absorber in the terahertz band [26]. Moreover, people moved further and also explored the metamaterial-based absorbing structures in the visible and infrared spectrum. They used different types of plasmonic materials to explore the applications of metamaterial absorbers in solar photovoltaics and thermal emission. Hung et al. proposed an ultra-wideband metamaterial absorber for the visible light spectrum [27]. Cui et al. also presented the wideband metamaterial absorber for visible light applications [28]. All the aforementioned reported metamaterial-based absorbers have fixed operating frequencies and are designed/fabricated on rigid/solid substrates. Therefore, these features (fixed frequency and solid substrate) restrict their use to tunable and reconfigurable devices. Furthermore, these presented metamaterial absorbers cannot be used for cylindrical and spherical surfaces.

3. Tunable Absorbers

As the researchers discussed earlier, due to the fixed operating frequency of most of the available metamaterial absorbers, they cannot be integrated/implemented with tunable and reconfigurable microwave and optical devices. Therefore, there is a strong need to study and investigate the design methods of tunable and reconfigurable metamaterials. A different type of tuning strategy can be used to implement the tunable metamaterials, depending on the operating spectrum of the discussed metamaterials [14][29][30][31][32]. In the microwave regime, active elements (PIN & varactor diodes) are used to tune the operating frequency and steer the beam of the metamaterial-based structure [14]. Zhao et al. investigated tunable metamaterial absorbers with the integration of a varactor diode. They tuned the absorption peak of the proposed metamaterial absorber by actively controlling the reverse bias voltage (capacitance) of the participating varactor diode [14]. In addition, a tunable metamaterial absorber is also presented in [29], which is designed for microwave frequencies. The operating frequency of this absorber is also reconfigured through the inclusion of a varactor diode in the geometry of the metamaterial. Furthermore, tunable metamaterial absorbers can also be developed for terahertz bands. In the terahertz band, usually, graphene and phase-change materials are employed to design tunable metamaterial-based devices [30][31][32]. Huang et al. proposed a tunable metamaterial absorber, by captivating the phase changeability of a dielectric material, strontium titanate (STO), which changes its permittivity with the influence of varying temperatures [30]. Next, Lei and his colleagues studied the thermally tunable metamaterial absorber by embedding a phase-change material, vanadium dioxide (VO2), which changes from an insulating to a metallic state with the variation of temperature [31]. A graphene-based tunable metamaterial absorber is also designed in [32] for the terahertz band. Moreover, for visible and infrared metamaterial absorbers, tunable features are introduced by incorporating the phase-change material, germanium-antimony-tellurium (GST), or liquid crystal [33][34].

4. Flexible Absorbers

In addition to the tunable functionalities of metamaterial-based absorbers, the latest and most contemporary communication systems, and the areas of industrial growth in microwave and optical devices involve devices with diverse features of miniaturization, cost-effectiveness, and flexibility. For designing and implementing the flexible metamaterial absorbers, plenty of flexible substrates such as polyamide, polymer, paper, rubber, Kapton, etc. are used [35]. Until now, several flexible meta-absorbers have also been investigated, ranging from GHz to THz frequencies. The authors implemented the inkjet-printed absorber based on the silver nanoparticle, mounted over a flexible substrate of paper. This flexible absorber was designed for the x-band of microwave frequencies, and manifests a narrowband absorption peak at 9.09 GHz [36]. Furthermore, Hao et al. [37] also studied the dual-band flexible metasurface absorber for THz frequencies. They used polyamide substrate as a flexible dielectric material to attain flexible features. In addition to these flexible absorbers, many applications including radars and stealth, etc., required stretchable/flexible metamaterial absorbers to absorb the unwanted EM signals [11][38]. Riad and his team [39] designed the THz flexible absorber for infrared stealth applications. Similarly, Krzysztof et al. also implemented the flexible metamaterial absorber for the THz band. In this work, a simple and easily fabricable ring resonator was imprinted on the flexible substrate of polyimide [38]. Similarly, Tao et al. designed the narrow-band THz absorber, which worked on a single operating point of 1.6 THz [40]. By adopting similar methods, a highly efficient flexible metamaterial absorber can be designed for any desired operating frequency.

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