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METAMATERIAL ABSORBERS IN MICROWAVE AND TERAHERTZ REGIONS: A REVIEW

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Abstract- Metamaterials have become a significant topic of research in the recent years owing to their unique properties that are not found in naturally occurring materials. They have profound applications, one being the absorption of electromagnetic radiation. Generally, metamaterial absorbers consist of three layers. The top metallic layer is periodic in nature and its geometrical parameters are adjusted in such a way that the incident electromagnetic wave gets absorbed by the structure and prevents any reflection. The middle layer is dielectric layer which traps the electromagnetic waves and dissipates them as dielectric losses. The last layer is a metallic plane that prevents the transmission of radiation. This paper reviews the applications and the methods for designing metamaterial absorbers in the microwave and terahertz region. It presents a comprehensive review of the multiband, ultrathin, broadband, multilayer and graphene-based metamaterial structures with varying shapes, sizes and patterns in the microwave and THz regions.

Keywords: Metamaterial absorbers, Frequency Selective Surfaces, Terahertz absorbers, Broadband absorbers, Multiband absorbers, Ultrathin absorbers.

1. INTRODUCTION

In the 2nd half of 20th century there was a pioneering contribution to the field of electromagnetics in the form of metamaterials. Metamaterials are 3D structures that are deliberately designed to offer unique properties that are not seen in natural materials such as negative permittivity, permeability and refractive index, optical magnetism and anomalous reflection [1-3] in certain frequency bands. These structures have myriad applications, one of them being the absorption of Electromagnetic (EM) radiation. These absorbers are called as metamaterial absorbers which were first experimentally demonstrated by Landy et al. in 2008 [4]. It is a kind of filter that neither reflect nor transmit the electromagnetic waves in the desired frequency bands. The main advantages of metamaterial absorbers are compactness, ease of fabrication, light weight, polarization independence at broad frequency band and the ability to provide perfect absorption in a wide range of frequencies.

Metamaterial in microwave range is generally designed with split ring resonators and used for the enhancement of near field microscopy and imaging. The current review paper is mainly focused on the operation of metamaterials in microwave and THz region due to its wide range of applications like sensing, detecting, imaging, bolometer, etc. [4-6].

Due to its negative refractive index, metamaterials are employed for speedy detection and therefore find vast applications in biological sensing. As the electromagnetic waves strike the absorber, the wave attenuates and losses energy. This energy loss is due to the conversion from Electromagnetic Interference (EMI) energy to heat energy [7]. The amount of attenuation depends on frequency, permeability and permittivity of the material. However, the absorption of the absorber can be varied with the fluctuations in temperature of the environment is shown in [8-10], the behaviour of carbon nanotube and high temperature dielectric property in [11-13].

Due to all these unique properties, metamaterials are applied in many areas [14]. Acoustic metamaterial is designed in [15] which can reach unity absorption at those frequencies where the sound wavelength in air is three orders of magnitude greater than the membrane thickness. A multiband absorber with combined polarization sensitive and polarization insensitive, octaband and broadband for THz applications is designed in [16], [17] and [18] respectively. A plasmonic absorber is designed in [19] with quality factor and figure of merit of 120 and 110 respectively. This sensor operates as an effective refractive index sensor and shifts the wavelength of the absorption spectrum by 885 nm per refractive index unit (RIU). Tunable absorber is designed in [20] which can be useful for realization of frequency selective detectors for sensing applications. Metamaterial absorbers also provide the platform for the design of optical devices like filters, modulators, antennas, filters, etc. [21-23]. Graphene based MAs are also being developed absorber is designed with potential applications in optical storage, plasmonic switches, high performance filters and modulators [24]. MAs are also used for the design of communication equipment for Worldwide Interoperability for Microwave Access (WiMAX) (2.5/3.5/5.5 GHz) and Wireless Local

Area Network (WLAN) (5.2/5.8 GHz) applications [25]. Dual band absorption can be achieved by utilizing higher order harmonics or the combination of optical transmission and Fabry-Perot type cavity resonance in dielectric layer. For multiband, we can combine several metallic units in a single unit cell with different geometrical parameters. Similarly, for broadband responses, we can combine multiple single metallic unit with different geometrical parameters as the geometrical parameters of single unit in each unit cell determine the wavelength.

This review paper presents a comprehensive review of the multiband, ultrathin, broadband, multilayer and graphene based metamaterial structures with varying shapes, sizes, patterns and applications in the microwave and THz regions in terms of applications and designs. There are other review papers which focusses on the development of active metamaterials and meta-devices ranging from microwave to visible wavelengths [26], importance of metamaterials in the advancement of microwave sensors, photonic devices, antennas and energy harvesting [27], existing optimization techniques for low frequency perfect absorbers [28], theoretical models for THz regions [29], new types of chiral metamaterials [30], liquid crystal-based developments and novel applications [31].

1.1. Structure of a Metamaterial Absorber

Generally, most metamaterials consist of a metallic top layer and a ground metal plane separated by a dielectric substrate. The lossy dielectric substrate is used to absorb the electromagnetic energy and a perfect conductor is used as the ground plane to block the transmission. The top layer of the metamaterial consists of periodic arrangement of metallic structures called as unit cells whose period is much smaller than the operating wavelengths and its thickness, size and operational bandwidths are the important parameters.

Metamaterial absorbers [32-32] can be divided into two categories, those with metallic backing [34-36] and those without metallic backing [37-38]. Most of the MAs consist of split ring resonator (SRR) in the top layer with a metallic backing at the bottom [39]. Some MAs consists of composite structures like multiple resonators [40-41], stacked structures [42-43], multi-sized structure [44-45] and nano-wire arrays [46]. Stacked structures and nano-wire arrays may not always have a metallic backing.

1.2. Absorption Mechanism in Metamaterial Absorbers

The absorption mechanism can be explained by impedance matching theory. Since the incident wave is not reflected back, the first layer consisting of the metallic patterns should be designed in such a manner that their effective impedance becomes same as that of the medium from which the wave is incident. The first plane with the metallic patterns is considered as a single homogeneous medium with frequency dependent effective permittivity ε_{eff} and effective permeability μ_{eff}. The effective permittivity and effective permeability should be same for perfect absorbing region and impedance Z_{eff} is calculated from ε_{eff} and μ_{eff} and it matches to impedance of free space (Z_0) i.e., the relative impedance $Z = Z_{eff}/ Z_0 = 1$. The real part of Z is close to 1 and imaginary part is close to 0.

Electromagnetic absorption in the top metallic layer is negligible in most of the cases. Thus, the dielectric spacer plays an important role by providing the medium for confining the electromagnetic radiation and in dissipating it as dielectric losses. The thickness of the spacer depends on refractive index of spacer. Thin designs can be achieved by using dielectric spacers with high refractive index.

1.3. Organization of the Paper

The organization of the paper is as follows: the next section reviews the design of microwave MAs that exhibit multi-band characteristics. Also, ultrathin, multi-layer and graphene based absorbers are discussed in this section. The third section reviews the design of THz MAs that are multi-band, graphene based, ultrathin and broadband. The last section presents the conclusion of this review. It also presents the limitations of these designs and the future scope for research in this field.

2. MICROWAVE METAMATERIAL ABSORBERS

In this section, we have focused on various design strategies of MAs in microwave region like multiband, ultrathin, multilayer and graphene based absorbers.

2.1. Multiband Microwave Metamaterial Absorber

Single band T shaped absorber is designed in [47] with absorption rate of almost 100% at 10.19 GHz. A wearable microwave MA is designed in [48] for indoor radar applications consisting of two square ring resonators and substrate thickness of 1 mm which provides the dual band absorption. It exhibits two absorption peaks (> 90\%). As the size of pattern becomes large, high absorptivity band shifts to lower frequency. Also, this absorptivity performance is insensitive to the bending effect so this can be used for wearable applications.

In [49], a switchable MA is designed with an array of 19×19 unit cells using p-i-n diodes to control the RF signal. This microwave absorber can achieve two switchable operations, one covers from 0.85-1.88 GHz and the other from 2.66-5.23 GHz. Polarization independent triple band microwave MA is designed in [50] using polyethylene terephthalate substrate of thickness 0.32 mm. Three patterns (square, ring and semicircle) as shown in Figure 1 are combined and the absorption peaks get shifted due to mutual coupling thereby obtaining two high frequency bands along with enhanced bandwidth with 99.7%, 95.6%, 97.5% absorption rates at 9.1, 11.04 and 11.44 GHz, respectively.

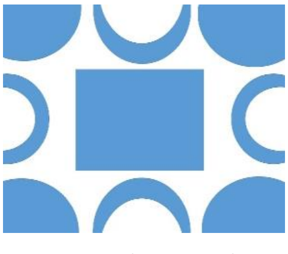

Figure 1. Unit cell configuration of absorber [50]

Quadruple-band MA is designed in [51], and consists of a copper pattern of thickness 0.017 mm on the top and bottom layer of FR4 dielectric substrate of thickness 0.217 mm. Four absorption peaks were obtained and the maximum absorption rate of 99.94% was obtained for 39.59 GHz while the minimum of 99.05% was obtained at 52.78 GHz. It is observed that the first two absorptions are more than 96% and there is almost no variation when incident angle is varied from 0 to 40. For TE polarization, with the increase in incidence angle, the absorptions of all the bands are 99.38%, 96.15%, 91.71% and 99.83% at 40. The absorption rate reduces from 99.47% to 92.17% when height of dielectric substrate is increased to 0.3 mm. The publication statistics for multi-band microwave MA obtained from the Scopus database are shown in Figure 2.

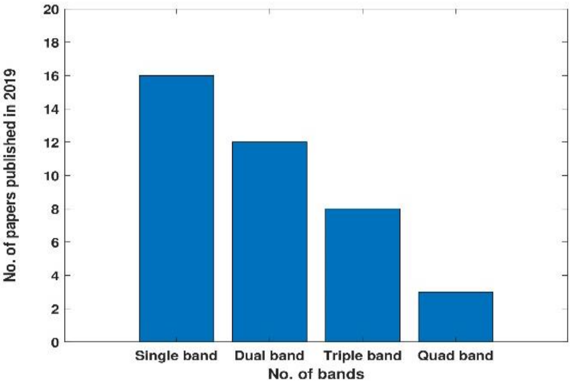

Figure 2. Publication statistics for multi band microwave MA

From the publication statistics, it can be concluded that single band absorbers are still being actively researched for microwave applications. Multi-band microwave MAs are of less significance to the research community.

2.2. Ultrathin Microwave Metamaterial Absorber

Researchers are now focusing in designing ultra thin MAs to minimize the space occupancy and for wideband applications. In ultrathin designs the thickness of the dielectric spacer is much lower than the wavelength of the incoming EM radiation.

An ultra-thin absorber consisting of three different structures, namely, T shaped, split-I (SI) and split Jerusalem cross (SJC) was proposed in [47] with a thickness of $\lambda/37$ where λ is wavelength of incoming EM wave. T-shaped absorber achieves absorption peaks at 10.19 GHz, split-I absorber achieves two peaks at 9.32 and 10.75 GHz and SJC absorber achieves five peaks with absorptivity as high as 99.9% at 10.93 GHz. The absorption response is same till 45 of incident angle and thereafter reduces to 60% of the maximum absorption rate for T and Split I shaped absorber. For triple band applications, SI shaped absorber achieves one more peak at 11.03 GHz by combining two resonating elements with the polarization angle of 60. In SJC absorber, the peak at 9.14 GHz increases with an increase in polarization angle but decreases at 9.92 and 10.93 GHz.

A MA is designed in [52] using two concentric circular split rings on the FR4 dielectric substrate which is compact and ultrathin ($\sim\lambda/15$). Numerical simulation was done using ANSYS HFSS and it was observed that absorption bandwidth above 90% lies between 7.85 to 12.25 GHz and two peaks are at 8.36 and 11.18 GHz with rate of 99.66% and 99.92% respectively. In [53], miniaturized MA is designed of size 20×20 mm^2 about $0.0036\lambda^2$ which is a quarter of the conventional UHF MA to enhance the performance of the RFID systems. MA is composed of top metallic square loop with lumped resistors (80 Ω) separated by the FR4 substrate. When the dimensions of MA are reduced, the resonant frequency shifts to higher side. In [54], high impedance surfaces are used to design thin MA as shown in Figure 3.

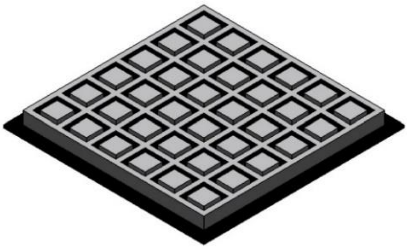

Figure 3. 3D sketch of the analyzed configuration [54]

FSS are designed by using periodic pattern through resistive inks avoiding the use of bulky lumped resistors.

In [55], MA is designed with a compact unit cell to decrease the operational frequency and sensitivity. The unit cell has 16-sided equilateral shape of size 20×20 mm^2 with 8 equal 100 Ω resistors. After modifying the structure, the frequency got shifted at 1.35 GHz. There is a variation of ±10% and ±20% as the height of spacer and resistance respectively are changed.

In [56], ultrathin and light weight MA with high impedance surface is designed by using cardboard, aluminum foil and spray painting which is a low cost fabrication process. It is used to limit the effects caused by interferences. The chosen waveguide is operating in the frequency band of 3.85-5.8 GHz with central frequency of 5 GHz. In [57], a Jerusalem cross resonator was modelled on a miniaturized unit cell, as shown in Figure 4, and was fabricated using inkjet printed silver nanoparticle which is flexible and eco-friendly.

Figure 4. Top view of unit cell of inkjet printed MA [57]

It can achieve the absorption rate at 9.09 GHz which is greater than 99% at the normal incidence. This small unit cell has high absorptivity for incidence angle up to 40. It exhibits resonance at 9.25 GHz with impedance equal to unity. It was fabricated and achieved over 90% absorptivity in 8.84-9.58 GHz and over 95% at 9.09 GHz for less than 30 angle of incidence. The publication statistics for ultrathin microwave MA is shown in Figure 5.

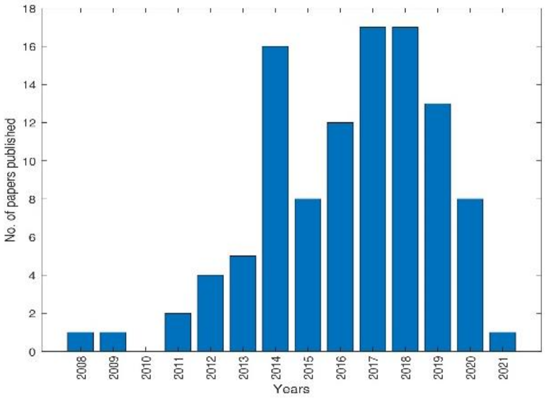

Figure 5. Publication statistics for ultrathin microwave MA

Ultrathin absorbers usually use dielectric materials with high refractive index, which reduces the dimensions of the structure. This also shifts the resonant frequency to the higher side. This may be the reason for decreasing trend in the published articles over the past few years, as most of the applications are in lower frequency regimes.

2.3. Multilayer Technology in Microwave Metamaterial Absorber

Single layer MA is designed in [58] in which 2D array of conductive cross dipoles with lumped resistors on the top of FR4 substrate is used to reduce the radar cross section as shown in Figure 6.

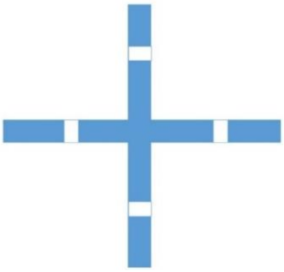

Figure 6. Side view of unit cell [58]

The height of the absorber is 0.077λ. Power loss density distributions are shown at 7.1 and 10.3 GHz and with the increase in frequency, the loss at the gaps between the conductor's increases. In [59], two-layer structure is designed by replicating the similar single layer structure with 1 mm air gap. The single layer absorber has two absorption peaks at 2.74 and 3.75 GHz whereas double layer has three absorption peaks at 2.74, 3.25 and 3.73 GHz. In [60], the MA comprises of split ring cross resonator with angular and polarization insensitivity using multilayer technology as shown in Figure 7.

Each cell comprises of an inductive and a capacitive meander line by which small sizes can be attained at the same resonance frequency. It results in high absorptivity at 10.28 GHz (97.5%), while impedance matching is attained at 10.28 GHz due to real values of the impedances. The publication statistics for multilayer microwave MA is shown in Figure 8.

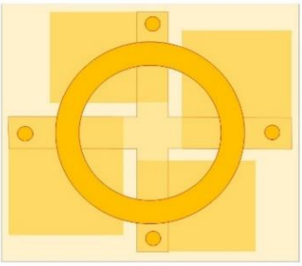

Figure 7. Top view of unit cell [60]

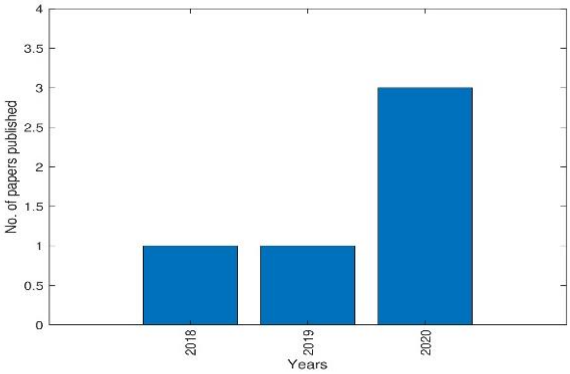

Figure 8. Publication statistics for multilayer microwave MA

It can be concluded that multilayer absorbers can be designed by using split structures and are useful for switching the absorption peaks and can be used for sensing applications. For multilayer absorbers, the loss at the gaps between the conductors increases with increase in frequency.

2.4. Graphene Based Microwave Metamaterial Absorbers

Graphene is a new type of 2D material consisting of only one layer of carbon atoms which has the advantage that the thickness of MA composed of graphene is thinner than that of composed of metal. It exhibits strong semi metallic properties because of its fermi level as well as conductivity which can be adjusted by external bias [61-63]. Its electrical conductivity can be easily tuned in a broad frequency range and its electrical tunability allows fast reflection or absorption modulation. The fermi energy E_F of graphene is shown by following equation [62].

$$E_F = \hbar v_f \sqrt{\frac{\pi \varepsilon_p \varepsilon_0 v_g}{e t_s}} \tag{1}$$

where, v_f is fermi velocity, ε_p is the relative permittivity, ε_0 is vacuum permittivity, v_g is the external voltage and t_s is the thickness of the plasma.

In [64], multilayer graphene-based frequency selective surface (MLGFSS) of size 150 mm x 150 mm is designed having applications in stealth technology to hide objects from radar detection. In cross shape pattern, the working frequency shifts from 11.9 to 13.2 GHz when compared from uniform graphene layer. The absorptivity can be managed by altering the sheet resistance of graphene layer. In Jerusalem cross pattern, it exhibits dual band absorption at 10.5 and 20.2 GHz at low sheet resistance. As the sheet resistance increases, the absorptivity increases.

To model graphene, its surface conductivity is given by Drude model [62-63].

$$\sigma_g(\omega) = \frac{e^2 E_F}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}} \tag{2}$$

where, $\tau = \frac{\mu E_F}{e v_F^2}$ is the carrier relaxation time, ω the angular frequency and E_F the fermi energy and μ is the mobility of electrons. The relative permittivity of graphene is given by [62-63]:

$$\varepsilon(\omega) = 1 + i\frac{\sigma_g(\omega)}{t_g \omega \varepsilon_0} \tag{3}$$

where, t_g thickness of graphene film.

The publication statistics for graphene-based microwave MA is shown in Figure 9. Graphene based metamaterial absorbers are best suited for stealth technology and their absorption spectrum can be easily changed with the Fermi level. However, the number of published papers on graphene-based microwave MA are few as compared to the other designs.

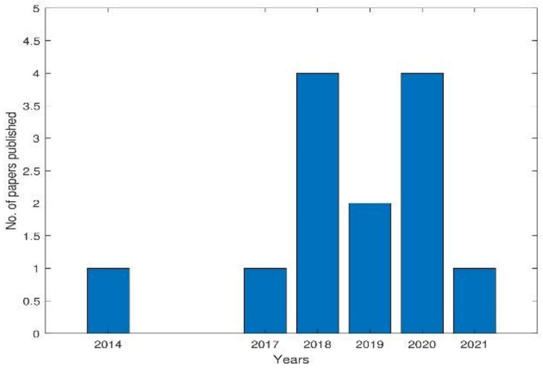

Figure 9. Publication statistics for graphene-based microwave MA

3. THZ METAMATERIAL ABSORBERS

THz MAs are receiving increasing attention from the research community in the recent years. This interest is sparked by the determination to close the infamous "terahertz gap". In this section different THz MAs are discussed.

3.1. Multiband THz Metamaterial Absorbers

MAs have attracted attention in terahertz band due to its application in sensing, detecting, bolometer, photodetector and imaging in recent years. MA has been now extended from microwave to terahertz, infrared and visible regions. A multiband THz super absorber is designed in [65] with square metallic patch and a small rectangular hole in it due to which we get three resonant band with absorption rate of greater than 95%.

A multiband (triple and dual band) absorber is proposed in [66] by using one planner metallic resonator. The authors have used the combination of indium tin oxide (ITO)-Polyimide-ITO, ITO-Teflon-ITO and ITO-polyethylene terephthalate (PET)-ITO to achieve a high absorption rate. A triple broadband is designed in [67] in four different configurations. The absorption (>80%) can be observed in three frequency bands, 142-159 THz, 183-200 THz and 233-245 THz respectively for all the four types of configurations.

The MA is designed in three different square gold patches and the absorption rates are compared, thereby obtaining three resonances with the center frequencies of 151, 191 and 240 THz respectively. It was also observed that the center frequency of the three bands changes below the incident angle of 10 but increases as the angle increases for both TE and TM polarization.

A triple broadband polarization sensitive MA for terahertz applications including sensing and imaging is designed in [68] and consists of metallic layers separated by GaAs which is ultra-compact (0.058λ) and ultrathin (0.028λ). The absorption peaks are at 1.71 THz, 3.16 THz and 4.89 THz with the absorption rates of 99.4%, 99.6% and 90.5%. A five-band terahertz MA is designed using concentric circular rings made up of metal in [69], and 5 absorption peaks are obtained. For the first, third and fourth peaks, the electric fields are concentrated at the edges of outer rings. Five band terahertz absorber designed in [70], comprises of three nested SRR which uses the hybrid of LC resonance and dipolar response of the structure as shown in Figure 10. Five absorption peaks with the maximum of 99.83% at 1.10 THz were obtained.

Figure 10. Structure of five band absorber [70]

In [71], six band terahertz MA is designed using cross-cave patch which exhibits six absorption peaks from 0.4 THz to 2.2 THz which can be tuned easily by varying the temperature. This MA has six distinct peaks at 0.908 THz, 1.192 THz, 1.493 THz, 1.611 THz, 1.901 THz and 1.962 THz with absorption rates of 98%, 99.6%, 95.2%, 97.9%, 96.7% and 99.9% respectively. When the external temperature changes from 190 K to 230 K, the six resonant frequency shift is about 55.3%, 30.4%, 19.1%, 16.7%, 12.1% and 11.5%. A six-band terahertz absorber is also designed in [72] based on three concentric circular split rings and a square split ring and all the absorption peaks are close to 99%. The six absorption peaks in this paper are at 0.3 THz, 0.6 THz, 0.816 THz, 1.56 THz, 2.259 THz and 2.52 THz for x-polarized and 0.6 THz, 1.4 THz, 1.6 THz, 2.1 THz, 2.25 THz and 2.65 THz for y-polarized. This design has the applications in imaging, detection and sensing. The publication statistics for multiband THz MA is shown in Figure 11.

From the publication statistics, it can be observed that unlike microwave MA, in THz, dual band absorbers are being actively researched. Multi-band characteristics can be obtained by using resonators of different sizes in a single unit cell. These resonators can also be placed in a concentric fashion to obtain such characteristics.

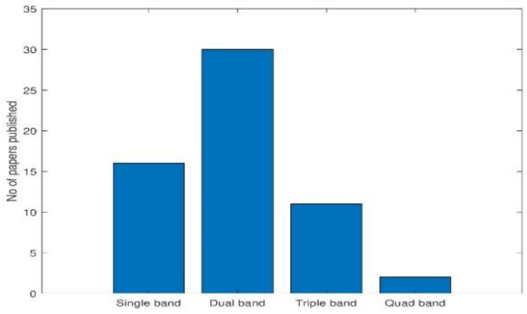

Figure 11. Publication statistics for multiband THz MA

3.2. Graphene Based THz Metamaterial Absorbers

In [73], Graphene nanoribbons are combined with rings to design a multiband absorber with the absorption rates of 99.8%, 98.4% and 65.7%. The absorber supports only one peak for the individual configurations of the nanoribbons and ring and three peaks when they are combined. A broad dual band switchable graphene-based terahertz MA, having wide angle characteristics, is designed in [74]. This designed MA is independent of the polarization. The relative bandwidth reaches 97.8% and 31% with the absorption rate of 80% in the frequency range of 0.473-1.407 THz and 2.273-3.112 THz respectively.

Ultrasensitive dual band terahertz absorptive paired-ring micro-fluid sensor (APRMS) polarization insensitive metamaterial is designed in [75]. As the refractive index (n) is made to vary from 1.0 to 2.1, the absorption peaks are first observed to increase and then decrease. Graphene based MA is designed using dual ring structure as shown in Figure 12 for terahertz application in [76] and has absorption at 1.6 THz and 2.89 THz. Due to the first absorption peak at 1.6 THz, the electric field is formed on the outer ring and for second peak at 2.89 THz, it is formed on the inner ring.

Figure 12. Top view of ring-based MA [76]

The author has also demonstrated the dual ring complementary MA with three absorption peaks at 2.25 THz, 4.18 THz and 5.2 THz having the absorptivity rates of 87%, 89% and 92% respectively. A dual band MA is designed in [39] consisting of electric SRR layer and metallic layer separated by a spacer. This absorber shows two distinct absorptions near 0.45 THz and 0.92 THz.

The authors have designed a MA with high electronic mobility transistor (HEMT) having the ability to attain both high modulation speed as well as depth. In [77], graphene-stack-based absorber is designed in which the absorption rate can be controlled by changing the gate voltage on graphene stack cavity. The publication statistics for graphene-based THz MA is shown in Figure 13.

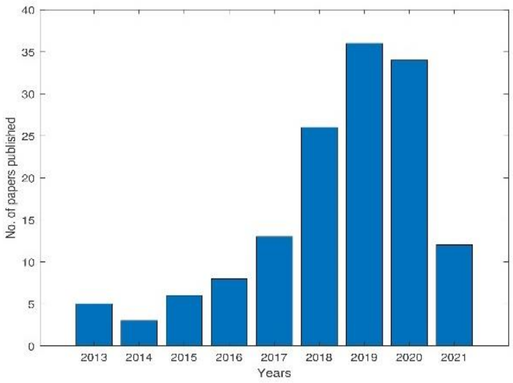

Figure 13. Publication statistics for graphene-based THz MA [77]

The publication statistics show that graphene is prominently used in THz designs as compared to the microwave counterparts. These are usually designed using ring resonators as graphene exhibits high electron mobility and conductivity. The other reason for their prominence is the ease with which the spectrum can be shifted by changing the Fermi level of graphene or by applying an external magnetic field.

3.3. Ultrathin and Broadband THz Metamaterial Absorber

An ultrathin ($\sim\lambda/24$) broadband MA using SRR and cross slot structure is designed in [78] which results in 90% absorption rate in the frequency band of 42 THz to 53 THz. A maximum of 99.5% absorption is obtained in the frequency range 46 THz to 47.6 THz. The electric field and magnetic field are concentrated at the edges and surfaces of the ring and cross respectively. An ultrathin MA having thickness lesser than 240 times the absorption wavelength is designed, using four connected SRRs, in [79]. There is nearly perfect absorption peak at 250 MHz with absorption rate of 99.3%. A polarization insensitive ultrathin ($\sim\lambda/6$) metasurface THz absorber is designed in [80] consisting of supercells of fractal crosses which achieves a broad absorption bandwidth of one octave.

Broadband THz triple layer MA is designed in [81] based on nested circle rings as shown in Figure 14 which achieves the broadband absorption of more than 90% in the frequency range of 1.666 THz to 2.562 THz.

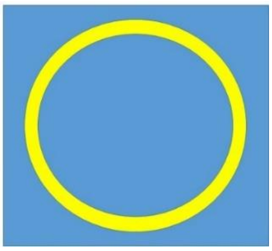

Figure 14. Structure of MA unit cell [81]

The resonant frequencies are located at 1.724 THz, 1.906 THz, 2.168 THz, 2.45 THz with the respective absorptivity's of 97.41%, 99.94%, 98.94% and 97.78%. The MA is well maintained till the incident angle increase up to 60. The broad bandwidths of the single, double and triple layers are 0.514 THz, 0.718 THz and 0.896 THz respectively. In [82], the authors have designed the ultra-wideband MA by using the mixture of copper and GaAs on the top layer which can enhance the bandwidth (98-152 THz) and absorption rate (90%). An ultra-wideband MA is proposed in [83] using upper metal plate designed by fractal and bottom metal reflector with an operating range of 6.39 to 9.47 THz. A miniaturized MA in THz range is designed in [84] by using a square loop enclosing two concentric cross-shaped loops provide 98%, 96% and 98% absorption at 0.33 THz, 0.62 THz and 0.82 THz. The publication statistics for ultrathin and broadband based THz MA is shown in Figures 15 and 16, respectively.

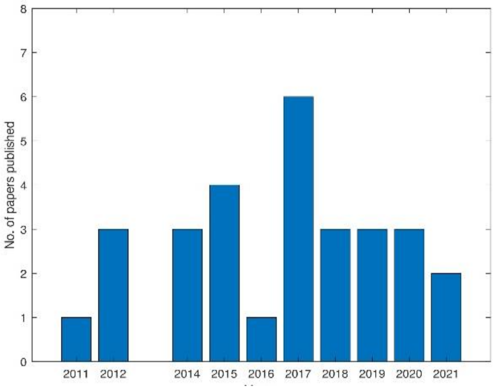

Figure 15. Publication statistics for ultrathin based THz MA

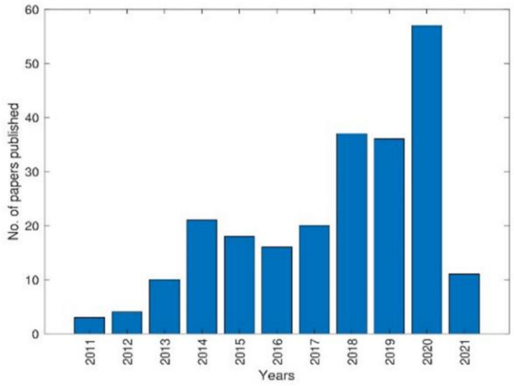

Figure 16. Publication statistics for broadband based THz MA

It can be concluded that the ultra-thin absorbers having thickness less than 240 times of wavelength can be designed using connected SRRs [82-84]. Broadband polarization insensitive THz MA can be designed by using nested rings [85] or nanotubes [86], which can achieve absorption rate of more than 90%. In [87], a tunable broadband MA is proposed based on Fabry-Perot cavity in the terahertz region with a absorption rate over 90% with a central frequency of 2.645 THz.

4. CONCLUSION AND FUTURE WORKS

In this review work, the design and application of MAs in microwave and THz region has been discussed. From the applicability viewpoint, microwave MAs have played an important role in the reduction of radar cross section (RCS), improvement in the performance of the RFID systems, designing of waveguides and resonators and in improving the antenna technology. THz MAs have important applications in thermal emission, sensing, imaging, photo-detection, stealth technology, solar energy harvesting, etc.

For perfect absorption, the impedance of the top metallic layer should match with the free space impedance. Multi-band absorption can be achieved by adding resonators of different sizes to the metallic layer and by vertically assembling multiple metal dielectric layers. Multi-band absorber has many drawbacks like large unit size and difficulties in fabrication. To design simple multi-band absorbers without incorporating multiple resonators is a daunting task, which is being actively explored by the researcher community. To enhance the bandwidth multiple sized resonators can be used in a single unit cell. Also, stacking of layers can enhance the bandwidth. However, stacking increases the thickness of the absorber and its weight. It is also difficult to achieve high absorption over the entire broad band particularly for THz MAs. Another alternative is to use lumped elements like resistors to broaden the bandwidth at microwave frequencies. Designing thin broadband structures is an interesting topic for future research.

For practical applications, it is not possible to always have normal incidence. The polarization of the incident EM field may also vary. Thus, it is extremely challenging to design structures whose absorption characteristics do not vary with the polarization and with the angle of incidence. The structures can be rendered polarization insensitive by having symmetrical designs. Exploring simple designs that can absorb EM for all incident angles is an interesting research topic.

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