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A REVIEW ON THE PURSUIT OF AN OPTIMAL MICROWAVE ABSORBER

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Abstract. *Mitigation of the electromagnetic radiations is essential for reliable communication of information. The challenges lie in achieving sufficiently good absorption over a broad range of frequencies. Considering the applications in airborne and handheld devices where light weight, thin, conformable and broadband absorbers are desired,* numerous techniques and methods are applied to design broadband absorbers. *In this review paper, a detailed analysis on electromagnetic absorbers including evolution, the materials used, and characteristics such as absorption efficiency over the years is presented. Progress on recent research on various polymer- based and metamaterial- based microwave shields are included along with their findings. Several prospects such as broadbanding, flexibility, multibanding are described here. Various material and structural composition offering good absorption performance in different frequency bands are also summarized whose the techniques can be used for suppressing electromagnetic interference and radar signature. The paper specifies the aspects one encounters while designing and realizing a perfect microwave absorber. Explored here are several works of distinguished authors which are based on various techniques used to achieve good absorption performance with ease of mounting.*

Key words: *absorber, electromagnetic, metamaterial, microwave, bandwidth*

1. INTRODUCTION

Electromagnetic emissions are usually generated and transmitted during the operation of wireless and electronic devices. Beyond a certain level, these emissions cause operational interferences and are classified as Electro-Magnetic Interferences (EMI**)**. Growth in modern high speed electronic devices packaged alongside the electromagnetic wave emitting sources in devices such as cellular telephony, wi-fi, bluetooth, etc. are posing newer challenges for the designer. In addition, these multitude of applications have created an

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even more congested electromagnetic environment leading to operational challenges of systems in close proximity [1]. The electromagnetic vulnerability and radiation hazard have to be controlled for obtaining an electromagnetically compatible (EMC) environment by reducing EMI. Microwave absorbers/shields are generally used to sufficiently reduce EMI.

Traditional microwave absorbers can be dielectric, magnetic or magneto-dielectric. The structures consist of one or more filler materials reinforced in a matrix material thus forming a composite with or without a metal back. The electrical or magnetic properties of these materials can be altered to achieve high absorption (reflection loss) over broadband frequencies. Although dielectric microwave absorbing materials achieve good absorption performance, however, thickness of the absorber increases by many orders to get good attenuation. For effective absorption there should be minimum reflection from the absorber surface. When the two reflected waves are out of phase they cancel each other and so reduce reflection. This is possible if the two waves destructively interfere, i.e., have a path difference of $\lambda / 2$. Since the wave travelling twice the thickness of the absorber (t) is equal to odd multiple of $\lambda_g / 4$, where, $\lambda_g = \lambda_0 \ / \ (|\varepsilon_r||\mu_r|)^{1/2}$ where, $|\varepsilon_r|$ and $|\mu_r|$ are the moduli of complex permittivity (ε_r) and complex permeability (μ_r) respectively. The magnetic component of absorber improves matching at the air-absorber interface ($Z' = \sqrt{\mu/\varepsilon}$). Magnetic losses along with dielectric losses enhance attenuation of the incident wave resulting in reduced thickness of the absorber as the guide wavelength reduces by a factor of $1/\sqrt{\mu\varepsilon}$. Magnetic materials offer an effective way of alternating electromagnetic waves by way of better impedance matching at the interface of the absorber and also reducing its thickness.

Then, there are metamaterial absorbers which are artificially engineered homogenous materials consisting of periodic unit cells that possess electromagnetic characteristics not found in natural materials [2]. The word "meta" means *beyond*, and "metamaterials" stand for the artificial composite materials. The homogeneity condition is attained by realizing the dimension of the unit cell size (a) much smaller than the wavelength of the incident wave in the guided medium and the effective homogeneity condition is satisfied for $a \leq \lambda_g/4$. The structure consists of top and bottom conducting layers isolated by a dielectric interlayer. The dielectric layer in the middle controls the input impedance and impedance matching, yielding to equivalent inductances (L) and capacitances (C) which form a LC equivalent circuit. Since both electric and magnetic fields are involved in *em* wave propagation, permeability (μ) together with permittivity (ε) plays an important role in absorber performance.

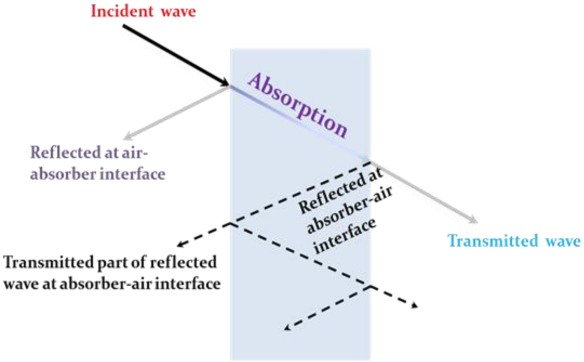

Fig. 1 Schematic representation of absorbing type EMI shielding mechanism

A schematic representation of the various wave components involved in absorption is shown in Figure 1. Design of microwave absorbers with enhanced absorption performance requires two important conditions to be satisfied: impedance matching characteristic and attenuation characteristic. When electromagnetic wave is incident on an absorber, reflection takes place at the free space-absorber interface due to mismatch in impedance. Reflections can be minimized if impedance of the absorber is matched to the free space impedance, resulting in penetration of the wave into the absorber, which is the first condition. Within the absorber, dissipation of radio frequency (RF) energy is maximized resulting in rapid attenuation of the amplitude as it propagates in the absorber structure. This is the second condition.

Hence, in this review, an effort has been made to describe the need of a polarization insensitive microwave absorber offering optimal broadband absorption up to a wide angle of incidence with minimum thickness, as well as cost.

2. ABSORBERS - THE ARCHIVES

Investigations on electromagnetic wave absorbers started in the Netherlands with the first known absorber being patented in 1936 which was a quarter-wave resonant type structure comprising of carbon black (CB) and TiO_2. Carbon black provides the dissipation, and a high dielectric constant can be achieved using TiO_2 for reduced thickness [3].

Absorbers were first used practically during the World War II (1939-1945) where Germany used two types of absorbing materials for camouflaging of submarines and periscope [4, 5]. One of them is the “Wesch” material in the form of a rubber sheet of about 0.3 inches thickness infused with carbonyl powder of a grid-like structure resonating at 3 GHz. The other is the “Jauman” absorber of about 3 inches thickness consisting of rigid plastic and resistive sheets placed alternately with decreasing resistances providing a gradual transition from a low to a high loss medium with a reflection loss of more than -20 dB over the range of 2-15 GHz.

It was during this period when J. L. Snoek explored the possibility of ferrite to be used as absorber [6]. During 1941-1945, materials known as “HARP” (Halpern-anti-radar-paint) were used by the United States for airborne and shipborne applications in the X-band. Reflection loss of the absorbers used were in the range of 15-20 dB at resonance. The absorbers which were used for air-born environment contained disc shaped aluminum flakes (high dielectric constant of 150) infused in rubber and CB where as the absorbers used for ship borne environment consisted of a high concentration of iron particles binded by neoprene rubber (dielectric constant of 20) having thickness of 0.025 inches and 0.07 inches respectively. The magnetic permeability of the iron shows resonance behavior at such high frequencies.

Around that time, another absorber, commonly known as Salisbury screen absorber, was also developed in the Radiation Laboratory [7]. A quarter-wavelength absorber having a resistive sheet (clothes coated with graphite) of around 377 ohm located at a distance of quarter wavelength behaved as a resonating structure. This arrangement where at one side of a slice of 0.75 inches thick wood a resistive cloth (known as Uskon cloth) was adhered and metal foil to the other side, showed resonance at 3 GHz with absorbance over 20-30 % of the frequency range when used practically.

Simultaneously, structurally modified absorbers were being investigated by the Radiation Laboratory. It was observed that reflections were reduced to normal incidence while using long pyramidal shaped absorber structures due to absorption of multiple reflections generating in the direction of the vertex of the pyramid. Proper impedance matching can be achieved by using graded and tapered absorbers as they provide progressive transition of the impedance [8-11]. Broad banding was experimentally achieved by many organizations using several structurally modified absorber surfaces such as cones, hemispheres and wedges. Few filler materials included carbon, graphite, iron oxide, powdered iron, aluminum and copper, steel wool, metal wires, etc. which were loaded into plaster of paris, various plastics and ceramics to be used as free-space absorbers.

3. TRADITIONAL ABSORBERS - BROAD BANDING ASPECTS

In the early 1950s, the commercial "Hair" broad-band absorber was manufactured by drenching animal hair into carbon black by Emerson in the US. The absorbers were 2 inches, 4 inches and 8 inches thick attaining a reflection coefficient of around -20 dB for normal incidence over the frequency range of 2400-10000 MHz, 1000 MHz and 500 MHz, respectively. Buckley at Emerson & Cuming, Inc. redesigned the hair absorbers to show an improved performance of -40 dB reflection coefficient when the front surface is convoluted. A schematic of the first Dallenbach layer magnetic absorber, shown in Figure 2, was patented using ferrite materials [12]. In the course of this period, Meyer, a German scientist presented few innovative concepts associated with microwave absorption such as resistance loaded loops and dipoles, slotted resistive foils, strips of magnetic & resistive materials with different inclinations, magnetic loading etc. This is how research into frequency selective surfaces (FSS) aspects came into being.

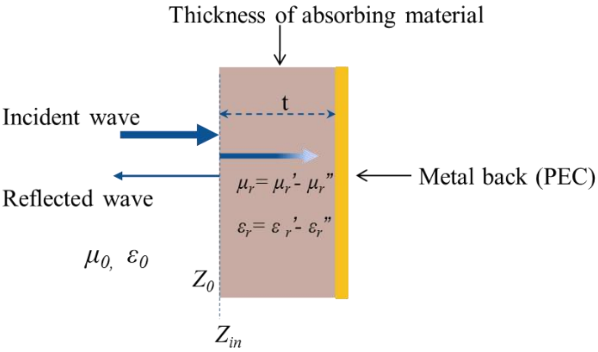

Fig. 2 A schematic of single layer Dallenbach absorber

Magnetic materials as possible absorber's fillers were inspected continuously during 1960's and 70's [13]. In the late 1960's, Suetake in his patent described a broadband absorber structure of thickness 12.3 inches comprising of a graphite-made zig-zag wall inclined at the front of a ferrite plate with reflective coefficient less than 0.1 in the frequency range of 0.1 to 1 GHz [14]. Also, absorption was controlled by coating several structured absorbers such as foams, netlike or honeycomb structures with some paint-like material containing carbon particles or fibres, or alloys of different metal like nickel chromium alloy, etc. [15]. Another type of absorbers employing plasma as the absorbent which could be generated by a radioactive substance requiring about 10 Curies/cm^2 was studied by M. E. Nahmias in his patent, which was a conjecture by then [16].

Evolution in the material aspect as inclusions and also in design process were the key factors of 1980's in absorber development. Jaumann absorbers were modified in design point of view by using graded layers so as to achieve high absorption bandwidth. Theoretical design of absorbers saw the rise in this era using computational models like transmission line models, Floquet theorem to calculate reflectivity from material properties and to study periodic structures, respectively. Dielectric materials were renovated by including fillers like rods, wires, disc, etc., which exhibited promising results and also conducting polymers, such as low-density polyacetylene, which were all studied as a possible candidate for absorption [15, 17]. In the year 1988, experiments conducted by the Department of Defense, US related to RCS reduction validated the use of a class of Schiff-base salts by dissolving in aircraft structural materials. This substance which was much lighter than ferrites had been used as radar absorbing paint for stealth aircrafts [18]. Chiroshield, a thin Salisbury shield made of chiral materials was introduced in 1989, offering increased absorption rate with low thickness for a wide range of frequencies compared to the conventional ones. Either Chirality could be incorporated into the prevailing materials or new chiral composites could be fabricated. There is a mutual coupling and induction of electric and magnetic fields within a chiral medium and the losses in permittivity imitate losses in permeability and vice-versa [19].

Many optimization techniques such as genetic algorithm was used to optimize the structures of Jaumann absorbers along with deep research into circuit analog absorbers, and FSS, to continue in the 1990's. Absorber composites made with different fibres or net-like structures being coated with conducting polymers were also on the rise. Tunable resonant absorbers made of conducting polymers were also investigated by varying the resistive and capacitive elements in the absorber until 1991 when carbon nanotubes (CNTs) came into light which were discovered by Lijima [15, 20]. Thus, CNTs paved the foundation for a new type of radar absorbing materials which consists of nanoparticles. Until the invention of CNTs, carbon fillers such as carbon black, graphite, expanded graphite, etc. continued to be used as radar absorbing materials. Single-walled and multi–walled CNTs have been extensively utilized showing wide microwave absorption. High absorption properties could be achieved by using a low weight percentage of CNTs because of their high aspect ratios (= length/diameter) which helps in attaining low percolation threshold at very low loading [21]. In addition to CNTs, their 3D structures such as graphene nanosheets, graphene oxide and reduced graphene oxide have also been prepared using different chemical methods of preparation for radar absorber applications [22].

Being light weight, flexible, corrosion resistant makes graphene one of the attractive materials to be used as a component of EM wave absorbing materials like any other carbon-based materials which possess extraordinary advantages of low density, high thermal stability and high chemical [23, 24].

Unfortunately, the direct application of graphene in EM absorption is restricted due to its high ε_r value which causes impedance mismatch [25, 26]. Efforts have been made to improve matching by mixing them with different magnetic fillers [27] and by using modified graphene (RGO). But this also resulted in some other downsides, such as aggregation, restacking, and the need of high filler content, which again hampers the practical applicability. Then, the concept of ‘plainification’ appeared where instead of adding more amount fillers, an interface type of structure is included to achieve superior properties [28–30]. This required fine adjustment of the structure and the process remains challenging.

Recent study on development of em shielding materials based on plant based cellulose nanofibres have shown the path of using environmental friendly materials. The material is a light weight, conductive and porous cellulose- polyaniline aerogel with a thickness of 5 mm which shows 95% absorption in the X-band and a real time heat dissipation behavior using a mobile phone with a great prospective for applications in portable electronics [31].

Lately, studies related to wear-on-body microwave communication have been introduced where textiles are coated with em shield materials so as to prevent any adverse effect of using electronic devices on our health. With a thickness of 2.236 mm, coating layers of composites where conductive polymer mixtures incorporating metallic nanoparticles, nanowires or carbon based nanostructures along with conventional textiles are used [32, 33], which provides shielding effectiveness of more than 20 dB over the X-band. Nevertheless, including such coatings on textiles still remains a challenge due to conformability and washability issues.

An interesting approach towards tunable absorbers was experimentally studied by Estevez et al. where two different hybrid fillers (CNT/AW and rGO/AW nanowires) were bound by silicone resin in X-band. The polarization loss originating from the interfacial polarization relaxations at the interfaces of CNT-resin & CNT-wire leads to higher dielectric losses. The domain wall motion due to the wires leads to the ferromagnetic resonance and contributes to the magnetic losses. Tuning of the absorber is thus controlled by the amount of CNT coating which guides interfacial interactions. A high reflection loss of -35 dB is obtained for rGO coating thickness of 2.7 mm at 11.3 GHz [34]. Tunable em wave absorption and shielding was achieved at a thickness of 1.65 mm by growing cobalt nanoparticles embedded variable length CNTs on natural cotton using CVD method. The highly elastic and easily compressible absorbers are light weight showing absorption intensity as -43 dB and also shields 99% of incident wave over a bandwidth of ~5 GHz in the frequency range from 2-18 GHz. CNTs with shorter length and less conductivity is favorable for microwave absorption, whereas with longer CNTs the conductivity increases which enhances the shielding effectiveness [35].

4. METAMATERIAL ABSORBERS - THE ORIGIN

In the quest of a perfect absorber, the use of metamaterial provides an encouraging solution to the problem of electromagnetic interference. Metamaterials are usually structured geometrically as a periodic arrangement of unit cells (metallic or dielectric elements) demonstrating wave characteristics that do not exist in nature and thus are often described as artificially engineered homogeneous medium [2]. Depending on the size and shape (geometry) of the unit cells, the electromagnetic properties such as permittivity (ϵ) and permeability (μ) can be altered to a wider range including negative values.

Developing thin metamaterial absorbers possessing characteristics such as conformability and fabricability with high absorption over a wide bandwidth is still in progress. Few pioneering works in this field is discussed here, starting with the origin of concept. It was in the years 1996 and 1999, when John Pendry along with his group, first experimentally realized the concept of negative permittivity and negative permeability respectively. Absorption in metamaterial-based absorbers is of a resonant type and the frequency is regulated by the rise of inductance and capacitance due to the dimensions of unit cells of the structure. The first metamaterial absorber was based on split-ring resonator (SRR). An array of SRRs were placed periodically in x-z plane on a resistive sheet of 1mm thickness providing a resistance of 377 Ω like Salisbury screen with minimum S_{11} being observed at around 2 GHz [36].

Then, the idea of electric ring resonator (ERR), also known as electric field driven LC resonator (ELC) based absorbers was presented, where at the top of the surface the incident E-field causes the flow of current and it gets stored within the metallic patches producing inductance and capacitance. Here, FR-4 substrates are used as a dielectric material on top of which unit cells are patterned as shown in Figure 3. An absorption peak of 96% was observed at around 11.65 GHz [37]. Since these absorbers had less absorption bandwidth, a 3-D microwave absorber was then developed combining the ELC and SRR structures for broadband absorption which exhibited a peak absorption of 99% at 2.4 GHz [38]. The relatively thin λ/5 thickness of ELC-SRR structure in the propagation direction makes it more beneficial, when compared to the typical λ/2 or greater thickness of traditional foam pyramidal absorbers. Also, lumped circuit elements could be added to this structure to initiate tunability.

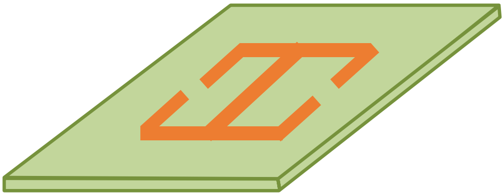

Fig. 3 A schematic of the unit cell in electric ring resonator (ERR)

4.1. Multiple banding

It was in the year 2010, when a triple layered unit cell structured metamaterial absorber was developed by Li et al., and a dual band resonant behavior was observed at 11.15 GHz and 16.01 GHz with maximum absorption of 97% and 99% respectively [39]. The structure incorporates a cross-shaped resonator (CSR) and complementary cross-shaped resonator (CCSR) in one unit cell, to make it compact. It also displays improved impedance matching the free space due to the mutual coupling effect between the two resonators. The ohmic loss and the dielectric loss account for the absorption, since there exists electrical resonance which leads to ohmic loss. In 2013, Bhattacharyya et al. obtained a triple band polarization independent absorption by using different combination and size of square-shaped closed ring resonators [40]. The surface current distribution around the square rings control the overall permeability of the structure, thus leading to absorption at different frequencies. The absorber exhibited a triple band absorption response with one band lying in X-band and two in C-band. Likewise, an arrangement of concentric squares and circular rings explored the polarization insensitiveness with triple band metamaterial absorbers [41, 42]. To improve the absorption bandwidth, metamaterial absorber based on sectional asymmetric structures was realized using CST studio suite by Gong et al. [43], which had thickness of 1.9 μm and was composed of Au and Si_3N_4. Due to the resonant behavior of the metamaterial, these absorbers suffer from narrow absorption bandwidth, limiting their usage in applications. For broadband absorption multilayering is one of the techniques which is used in metamaterial absorbers also.

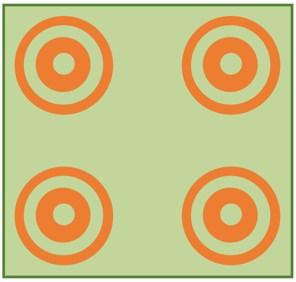

Fig. 4 Schematic of a donut-shaped resonator

Lee and Lee implemented multi-resonance structures of different geometric dimensions into a single unit cell to widen the working bandwidth. The structure is 0.8 mm thick and demonstrates a maximum absorption of 93% at 10 GHz with a bandwidth of 970 MHz [44]. The different mixture of unit cells with small difference in the scaling factor between cells having varying geometric dimensions when arrayed periodically demonstrates resonant absorption peaks overlapping and thus increasing the bandwidth. If the scaling factor between the cells increases, it shows split distinct resonant peaks. Dual and triple band metamaterial absorbers with wideband absorption was developed by Kollatou et al. by utilizing scalability property of metamaterials [45]. Special arrangements of donut-based resonators as shown in Figure 4 were also implemented in order to achieve multiband absorption. Multiple absorption peaks of 97%, 97%, 98% and 98% were observed at 6.5 GHz, 7.4 GHz, 9.2 GHz and 11.0 GHz respectively [46].

4.2. Broadbanding

Another technique for widening the absorption bandwidth was attempted by Gu et. al. where different sizes of hexagonal metal dendritic units are closely placed to combine absorption peaks of each unit an isotropic MA. Absorption greater than 80% is observed for normal incidence and oblique incidence for less than 45° in the frequency range from 9.05 GHz to 11.4 GHz [47]. As the unit cell of a symmetrical structure can resonate identically for different polarizations, there were several investigations on polarization insensitive absorbers using highly symmetrical structures, such as rotational structure [48], four-fold symmetrical structure [49], or higher order symmetrical structures [50].

Then, using the property of high absorption of magnetic materials a two-layered hybrid absorber was implemented by Li et al., where non-planar metamaterial was integrated with magnetic absorbing materials to observe 90% absorption over the range from 2 to 18 GHz [51]. The top layer is an arrangement of metal aluminium unit cells stacked on a metal backed magnetic layer which is composed of Carbonyl iron flakes powder infused in epoxy with a weight ratio of 2.65:1. Although the structure has the advantage of inheriting the characteristics of both magnetic absorber and non-planer metamaterial absorber for broadband absorption and absorption at lower frequency range respectively, the structure is quite complex so that might cause several fabrication errors. Following this, Yin et al. developed a less complex, polarization independent and thin broadband metamaterial absorber by using two tapered hyperbolic metamaterial waveguide arrays of different dimensions which has 90% absorption bandwidth from 2.3 to 40 GHz [52]. The absorption bandwidth is enhanced by appropriate selection of geometrical boundaries for each hyperbolic metamaterial waveguide connected in some pattern.

A wideband double layer circuit analog absorber involving an upper layer which contains an arrangement of resistor-loaded square loops printed on dielectric substrates was realized by Ghosh et al. The layers are separated by an air spacer adding to a total thickness of 4.6 mm. The bottom layer helps in increasing the total bandwidth and produces new resonance when the wave is incident normally. The absorber exhibits 90% absorption from 5.10 to 18.08 GHz. However, fabrication of such absorbers is difficult [53].

A wideband switchable metamaterial absorber was investigated by Kim et al. where lumped elements and microfluidic channels with liquid metal alloy are combined in order to reduce RCS for X-band and C-band [54]. The metamaterial absorber incorporated chip resistors and a modified Jerusalem cross resonator (JCR) which was adjusted by loading slotted circular rings into the whole structure. The JCR consists of slotted circular rings, resistors and microfluidic channels. The absorber was fabricated on a flexible substrate and the microfluidic channels are imprinted on a polydimethylsiloxane (PDMS) material. Absorption rate of 90% was observed covering almost the X-band from 7.43 to 14.34 GHz and the C- band from 5.62 to 7.3 GHz, with empty channels and liquid metal-filled channels, respectively.

Water has been used in designing microwave absorbers because of its frequency dispersive nature at microwave frequencies and also being abundantly available all over the world [55, 56, 57]. Following this, Yoo et al. designed a series of metamaterial absorbers with four different substrates, viz., FR-4, PET, paper and glass material in the frequency range from 8-18 GHz, using periodic arrangement of water droplets which actas a resonator [58]. Each droplet is placed on the top layer of the structure with proper height and diameter, controlling the absorption and bandwidth for an overall absorber thickness of 2.36 mm. Absorption rate of 93% on FR-4, PET, paper and glass substrates was observed in the frequency range of 8.3–12.07 GHz, 11.23–12.36 GHz, 9.2–16.5 GHz and 12.05–12.65 GHz, respectively. In another research carried out by Pang et al., where a water based metamaterial absorber of 3.5 mm thickness was used by incorporating water as a dielectric substrate [59]. The hybrid substrate being a combination of water and a low-permittivity material allows a leak-proof structure which can be easily fabricated presenting a 90% wideband absorption from 6.2 to 19 GHz. In one of the other works, distilled water filled dielectric reservoir based ultra-thin three dimensional water-substrate array organized periodically on a metal back metamaterial absorber were used. A triangular shaped metallic fishbone structure was also incorporated in between water-substrate and dielectric reservoir periodically attaining an ultra-broadband absorption in the frequency range from 2.6 to 16.8 GHz [60]. Recently, in the year 2019, a low cost flexible water-based metamaterial using 3D printing technology was proposed which offered 90% absorption over the broad frequency range of 5.9-25.6 GHz. The overall thickness of the structure was 4mm where distilled water was selected as the absorbing material and thermoplastic urethane was used to hold the water. The absorber is insensitive to polarization and shows good microwave absorption performance in wide-angle of incidence [61]. Another ultraband metamaterial absorber was presented where Tetramethylurea was added to water in order to alter the dielectric properties and this solution was used for absorption. The four-layered structure achieved an absorption of 90% covering the frequency range of 4.3 to 40 GHz [62].

An ultra-broadband polarization-insensitive metamaterial absorber was developed by Munaga et al. which presented 10-dB absorption bandwidth in C-band (3.78–8.28 GHz) during normal incidence with the incident angle less than 45° [63]. Further investigation on broadband absorber was done by Hoa et al. who reported a polarization insensitive absorber by incorporating a rotational symmetrical multilayer structure [64]. The absorber was based on periodic arrangement of metallic/dielectric conical frustums which show 90% absorption with large angle of incidence - up to 60°. Another four-layered 4.2 mm thick ultra wideband ionic liquid based metamaterial absorber was designed using 3D printing technology. [EMIm] $[N(CN)_2]$ was chosen due to its highly lossy nature which was injected in a periodic arrangement of photopolymer cylindrical array via 3D printing. Absorption rate of 90% was reported in the frequency range of 9.26–49 GHz along with good high absorption performance for oblique incidence of 45°. Using a low dielectric constant photopolymer material as a top layer, the impedance matching was improved [65].

A switchable C-band polarization insensitive absorber composed of a periodic arrangement of square loops along with PIN diodes to provide switching between single band and multiband absorption was reported by Ghosh et al. [66]. To provide bias voltage to all the switches a biasing network has been implemented without disturbing the resonance of the structure. The 4-axial symmetrical design of the structure provides polarization insensitiveness for all angles. The broadband switchable structure under normal incidence for OFF state exhibits 10 dB absorption bandwidth of 4.66 GHz (3.56 - 8.16 GHz), whereas for ON state good reflection value is observed for the whole frequency range.

A dual-band metamaterial absorber structure consisting of two circular rings showing absorption with oblique angles larger than 60° was designed and studied by Ayop et al. [67]. In the year 2016, another dual-band absorber symmetrical structure consisting of a rectangular ring, a cross and a slotted cross design was realized by the same team with angle of incidence of more than 77° with for X-band [68].

4.3. Conformability

Development of conformable absorbers is the need of the hour so that absorbers can be easily mounted on any surface. A flexible metamaterial absorber using printing technology was presented for cylindrical surfaces [69]. The unit cell of the absorber structure is based on JCR resonator which is printed on a flexible polymer polyethylene-terephthalate (PET) using silver nanoparticle ink. The structure shows 95% absorption at 9.21 GHz for flat, as well as a cylindrical surface having a diameter of 9.12 cm on a 0.62 mm thick substrate for all polarizations less than 30° of obliquely incident angles.

Few other flexible metamaterial absorbers were realized by many groups, such as a polarization incident 1.19 mm thick absorber designed on a flexible paper substrate based on inkjet printing technique substrate by Yoo et al. [70]. The inkjet-printed metamaterial absorber is fabricated on a paper substrate by applying silver nanoparticle ink using an inkjet printer. It offers 95% absorption at 9.09 GHz for all polarizations up to 30° of oblique incident angles. Then, Huang et al. observed a 90% absorption at both X & Ku bands when conductive graphene nano-flake ink is used to print an FSS on top of a flexible silicon dielectric material through stencil printing method [71]. The 2 mm thick structure enables conformable bending and provides a fractional bandwidth of 62% with an exceptional reduction in RCS. Using screen printing technique, another noted flexible metamaterial absorber for wearable device was designed on an ordinary textile using conductive silver [72]. The top of the unit cell of the structure was designed in the form of a channel logo and was backed by copper tape. The 1.2 mm thick absorber was simple to design and it presented the opportunity of integrating metamaterial absorber with wearable technology. The absorber showed good absorption at 10.8 GHz when the wave is normally incident. An interesting wideband textile based metamaterial absorber using the same technique was presented by Singh et al. as a wearable microwave absorber offering more than 90% absorption from 7.39 to 18 GHz. The top layer is the printed cloth of various kind (FR4, plain weave cotton cloth and twill weave cotton cloth), which is separated by a flexible dielectric foam from the ground plane in the 3 layered structure. The fabricated absorber was treated with polydimethylsiloxane (PDMS) to make it hydrophobic [73].

An X-band light weight metamaterial absorber using AgNW resistive film was described by Lee et al [74]. The structure which is 7.5 mm, consisted of cross-shaped resistive AgNW film on top of a styrofoam dielectric material backed by a conductor shows 90% absorption bandwidth from 6 to 14 GHz for all polarizations.

A graphite-based metamaterial absorber was designed instead of copper. As graphite has a low electric conductivity, high corrosion resistance, low density and high skin depth used to construct the surface pattern. A graphite square ring is placed on a layer of FR4 with an aluminium back offering an absorption bandwidth from 11.36 to 18 GHz [75].

Switchable metamaterial absorbers based on split ring resonator (SRR) were fabricated by 3D printing technology realizing single-band and dual-band switching, and three bands (4.5 GHz, 6 GHz and 8.8 GHz) simultaneous absorption for controllable absorption and selective filtering by rotating its units. For a single SRR unit, the main body of which is composed of polylactic acid (PLA) and the interior of the unit is hollow and filled with liquid metal to observe the regulation of absorption at the incident angle of 240° [76].

An ultra-broadband, light weight, magnetic metamaterial absorber consisting of periodically-arranged subwavelength-scaled stepped structure was designed and presented offering absorption from 1.23 to 19 GHz up to an incident angle of about 45°. Each unit-cell structure is made up of a mixture of carbonyl iron powder and resin and composed of four stacked cuboids of equal length and width. The magnetic loss of the magnetic material, the multi-resonances and the edge diffraction effects at different frequencies of the stepped structures contribute to a broad absorption band [77].

Until recently, there have been a number of investigations on microwave absorbers comprising of varying absorption levels, bandwidth and polarization independency over a wide-ranging angle of incidence with various thicknesses and few other parameters in different frequency ranges [78-88].

A comparison between the absorption, bandwidth, thickness, etc., of the few recently reported wideband microwave absorbers is listed in Table 1.

Table 1

Sl. No.	Type of absorber	Maximum Reflection loss (dB)	Frequency range (GHz)	-10 dB Bandwidth (GHz)	Thickness (mm)	Year	Ref
1	Dielectric	-53.9	2-18	4.56	3.5	2019	[25]
2	Dielectric	-62.25	8-18	6.64	2.7	2019	[26]
3	Dielectric	-32.0	8-12	4	5.0	2020	[31]
4	Magneto dielectric	-35.0	8-12	3.2	2.7	2018	[34]
5	Dielectric	-43.0	2-18	5.08	1.6	2019	[35]
6	Metamaterial	---	6-12	Multiple bandwidth	1.2	2013	[45]
7	Metamaterial	-10	4-12	Multiple bandwidth	3.1	2016	[53]
8	Metamaterial	-19.1	3.56 - 8.16	~5	1.2035	2016	[65]
9	Dielectric	-21	6.4-15	~8.5	1.0	2020	[89]
10	Magneto dielectric/ Hybrid	-20	8-12	~6	1.0	2019	[90]
11	Metamaterial	-16.42	4-8.12	~4.12	5.0	2015	[63]
12	Metamaterial	-20	4-10	Multiple bandwidth	1.035	2014	[91]

5. CONCLUSION

In order to design a microwave absorber, many challenging aspects, such as good absorption over a wide bandwidth, polarization sensitiveness for wide incidence angle, low thickness, conformability, etc. are to be considered. Some of these aspects with all the historical achievements on various conventional and metamaterial absorbers are discussed here. Different sets of materials, such as conductive and non-conductive polymers, magnetic and non-magnetic nano materials, along with techniques to maximize absorption bandwidth are considered here. Symmetrical structures using SRRs, FSS, varactor diodes, PIN diodes, lumped elements, fractal structures, multilayering, etc. are some research areas which are used recently to address polarization sensitiveness and incidence angles cases. Use of substrates which are magnetic, thermoplastic, water –based are also presented, as they not only maximize absorption efficiency but few are also easily moldable into thin sheets and mountable on any surface. In addition to the benefits and limitations, several critical aspects experienced in designing a near-perfect microwave absorber are analyzed in order to have an overview of the current scenario. There are numerous possible applications of microwave absorbers in various civilian and defense sectors. Pursuit of ultra-thin, compact microwave absorber with broadband behavior and justification of the need for perfectly thin economical absorber with enhanced features for more practical airborne applications is of great interest and still quite challenging.

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