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REVIEW PAPER

Metamaterials in Electromagnetic Wave Absorbers

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ABSTRACT

Stealth technology in terms of absorption of electromagnetic waves is a most valuable research area for military purposes. Development of radar absorbing materials (RAM) had been actively researched for a quite long time. In the RAM design, weight, thickness, absorptivity, environmental resistance and mechanical strength are the key factors and therefore development of RAM with low density and high strength is a challenging task. As an alternative, research interest has shifted towards radar absorbing structures (RAS) and metamaterial is one of the lucrative options for the development of RAS. Metamaterials are a new class of ordered composites that exhibit exceptional electromagnetic properties not readily observed in nature. Built from microstructure that is small compared to wavelength of operation, metamaterials can be designed with effective permittivity and permeability values that can be large or small or even negative at any selected frequency. In this review paper, we first place the stealth technology in brief and then concept of metamaterials in context of conventional materials. We then discuss reflection theory of metamaterials from stealth point of view. Next section deals with recent progress towards its application as electromagnetic absorbers and future prospects especially in higher frequency region.

Keywords: Metamaterials, electromagnetic wave absorbers, stealth technology

1. INTRODUCTION

Stealth technology is related to the detectability of a target by the radar. The detectability of the target is measured in terms of radar cross section (RCS). The RCS is a property of the targets size, shape and the material from which it is fabricated and is a ratio of the incident and reflected power. There are four methods of reducing the RCS; shaping, active loading, passive loading and distributed loading. Shaping is the primary method of reducing the back scattered signal. Although shaping is very important, it redirects the radiation through specular reflection hence increasing the probability of detection from bistatic radars. Active and passive loading aims to reduce the scattering from highly reflecting regions through the application of patches. Active materials detect the incident radiation and emit signals of equal amplitude and opposite phase to cancel the signal, while passive materials are designed to modify the surface impedance so as to cancel the scattered signal. The fourth method, distributed loading involves covering the surface with a radar absorbing material that has imaginary components of permittivity and/or permeability, i.e. the electric or magnetic fields of the radiation couple with the material properties and energy is consumed. The last method covers a wide range of materials and their compositions. Under the scope of this paper only metamaterials have been considered and reviewed.

Metamaterials are artificial materials and history of the artificial materials seems to be traced back when in 1898 Sir J. C. Bose published his work on rotation of the plane of polarization by man-made twisted structures. Which by today's definition were artificial chiral structures as chirality is defined as change of plane of polarization. Afterwards, there were several other investigators in the first half of the twentieth century who studied various man-made materials. In the 1950s and 1960s, artificial dielectrics were explored for light-weight microwave antenna applications. The interest in artificial chiral materials was resurrected in the 1980s and 1990s and they were investigated for microwave radar absorbers for stealth applications. As per the Veselago's theoretical prediction[1], constitutive parameters such as permittivity and permeability of artificial materials are simultaneously negative when electromagnetic waves propagate in such materials and orientation of propagation vector is in the left direction while in conventional materials propagation vector is oriented towards right. Therefore, such materials are also popularly known as left handed materials (LHMs) or metamaterials. Due to its unique features, LHMs have attracted the military departments for potential applications in stealth technology along with various other civil applications.

The current state-of-the-art materials shows that when LHMs are used in an electromagnetic wave absorber, better impedance matching can be realized, and the absorption bandwidth can be expended effectively[2]. This indicates that LHMs may become one of the materials used to design electromagnetic wave-absorbers with better absorbability. Review of application of metamaterials in electromagnetic wave absorption is briefed and on the basis of an amalgam of the special materials (polymeric and chiral) with artificial materials (metamaterials) a novel multilayer structure has been proposed for broadened absorbability and tailoring or electromagnetic properties in the present work.

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2. CONCEPT OF METAMATERIALS

Metamaterials is composed of its structural elements in the same fashion as matter consists of atoms. But, these structural elements are made of conventional materials that are of normal atoms. Accordingly, metamaterials represents the next level of structural organization and thus has its name. The metamaterials concept is illustrated in Fig. 1[3]. From the Fig. 1 it is apparent that metamaterials can have any size and shape of its structural element like split ring resonator, coupled split ring resonator, curved structures etc. It shows probable geometries of artificial atoms, and a material, which can be formed on a larger scale using such elements.

In most cases, metamaterials implies an important particular case: periodic lattice of identical elements and this is an analogue for crystal. Random or irregular arrangements, being rarely under consideration, correspond to amorphous substances.

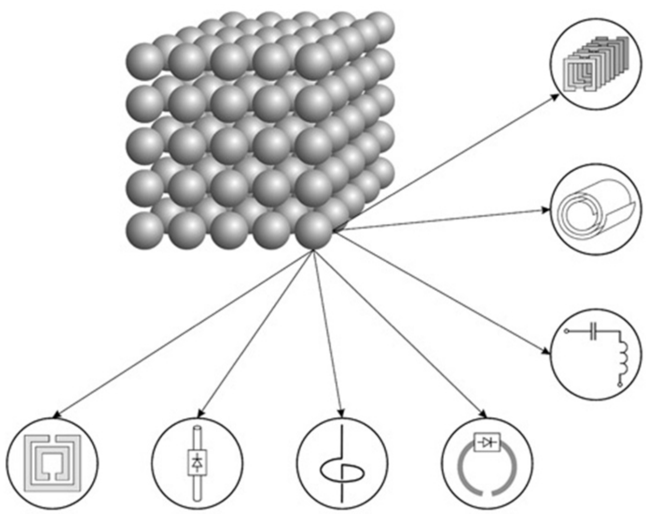


Figure 1. Illustration of metamaterial concept in terms of conventional materials[3].

For metamaterials, it is normally implied that user is interested in their response to electromagnetic fields. In contrary to the conventional materials, here, a response of the individual elements is also directly observable. Electromagnetic response implies merely how does the material affects the electric and magnetic fields to which it is subjected. Although the whole pattern of this influence is generally rather complicated, with the two responses being mutually dependent, delayed in time, spatially in homogeneous, nonlinear wrt field strength. The main effect of most of the materials can be reduced to linear modulation of the incident fields and can be described with corresponding material parameters: (electric) permittivity and (magnetic) permeability.

Material parameters depend on the scale they are considered on. If the wavelength is much larger than the atomic dimensions and inter-atomic distances, then the atomic behaviour has collective nature and material parameters can be introduced, substituting a huge number of separate element contributions with an effective medium response. For the corresponding set of problems, metamaterials are quite analogous to the normal ones and the same methods of analysis are applicable. When the wavelength is comparable with the scale of structure details, complex diffraction and scattering phenomena take place and there is no way to establish material parameters. Accordingly, in this range, metamaterials can be hardly treated as media. Finally, for waves with the length much shorter than the element size, the only characteristic of material that retains sense is the nature and density of the nuclei, with which electromagnetic quanta interact in a completely independent way. Therefore, concept of metamaterials loses its meaning and no analogy remains.

3. THEORY OF METAMATERIALS

Veselago theoretically investigated the electromagnetic properties of linear double-negative materials with negative permittivity and permeability simultaneously. He found that in such materials the electric field vector E, the magnetic field vector H and the propagation wave vector k of a plane electromagnetic wave form a left-handed system, but these materials otherwise are fully feasible and do not contradict the fundamental laws of electrodynamics.

Relative permittivity and relative permeability of lossy LHM can be expressed as $\varepsilon_r = \varepsilon_r^{\prime} - j\,\varepsilon_r^{\prime\prime}$, $\mu_r = \mu_r^{\prime} - j\,\mu_r^{\prime\prime}$. The propagation wave vector $k = k^{\prime} - j\,k^{\prime\prime}$ is given by[4]

$$k' = \frac{-\omega\sqrt{\varepsilon_r'\mu_r'}}{c}\sqrt{0.5\left[\begin{array}{l}1-\tan\delta_e\tan\delta_m\\ +\sqrt{\left(1+\tan\delta_e{}^2\right)\left(1+\tan\delta_m{}^2\right)}\end{array}\right]} \tag{1a}$$

$$k'' = \frac{\omega\sqrt{\varepsilon_r'\mu_r'}}{c}\sqrt{0.5\left[\begin{array}{l}\tan\delta_e\tan\delta_m-1\\ +\sqrt{\left(1+\tan\delta_e{}^2\right)\left(1+\tan\delta_m{}^2\right)}\end{array}\right]} \tag{1b}$$

where $k^{\prime}$ is the phase retarding per unit transmission distance when the wave propagates in the medium, which is called the phase constant; $k^{\prime\prime}$ is the attenuation level per unit transmission distance, which is called the attenuation constant; $\tan\delta_e$ is dielectric loss tangent given by $(\varepsilon_r^{\prime\prime}/\varepsilon_r^{\prime})$ and $\tan\delta_m$ is magnetic loss tangent given by $(\mu_r^{\prime\prime}/\mu_r^{\prime})$.

The impedance $Z = Z' - jZ''$ is given by

$$Z' = \sqrt{\frac{\mu_0\mu_r'}{\varepsilon_0\varepsilon_r'}}\frac{1}{\sqrt{1+\tan\delta_e{}^2}}\sqrt{0.5\left[\begin{array}{l}1+\tan\delta_e\tan\delta_m\\ +\sqrt{\left(1+\tan\delta_e{}^2\right)\left(1+\tan\delta_m{}^2\right)}\end{array}\right]} \tag{2a}$$

$$Z'' = \sqrt{\frac{\mu_0\mu_r'}{\varepsilon_0\varepsilon_r'}}\frac{1}{\sqrt{1+\tan\delta_e{}^2}}\sqrt{0.5\left[\begin{array}{l}-1-\tan\delta_e\tan\delta_m\\ +\sqrt{\left(1+\tan\delta_e{}^2\right)\left(1+\tan\delta_m{}^2\right)}\end{array}\right]} \tag{2b}$$

Figure 2 depicts the multilayer structure backed by a perfectly conducting plate. The total number of layers is N. $\varepsilon_r^{(n)}$ and $\mu_r^{(n)}$ are the relative permittivity and permeability of n^{th} layer. $d^{(n)}$ and $\alpha^{(n)}$ are the thickness and incident angle of the n^{th} layer. ε_o and μ_o are the permittivity and permeability of free space.

When plane wave is propagating in the multilayer structure, the reflection would be analyzed by transmission line model[5]. Parallel and perpendicular polarization reflection coefficients $R_{\|}$ and $R_{\perp}$ are given by[6]

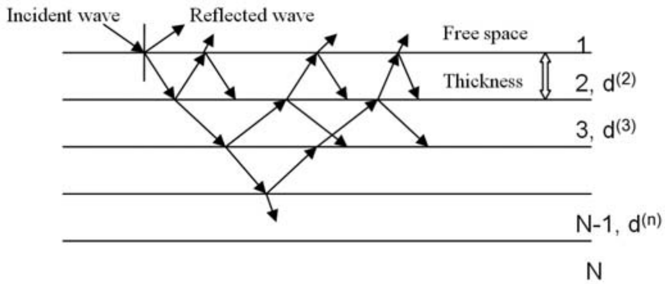


Figure 2. Multilayer absorbing structure backed by a perfectly conducting plate.

$$R_{\parallel} = \frac{Z^{(1)}Cos\alpha^{(1)} - Z_{i\parallel}{}^{(2)}Cos\alpha^{(2)}}{Z^{(1)}Cos\alpha^{(1)} + Z_{i\parallel}{}^{(2)}Cos\alpha^{(2)}}$$

$$R_{\perp} = \frac{Z_{i\perp}{}^{(2)}Cos\alpha^{(1)} - Z^{(1)}Cos\alpha^{(2)}}{Z_{i\perp}{}^{(2)}Cos\alpha^{(1)} + Z^{(1)}Cos\alpha^{(2)}} \quad (3)$$

where $Z_{i\parallel}{}^{(n)}$ and $Z_{i\perp}{}^{(n)}$ stand for the parallel and perpendicular polarization input impedance of the nth layer, given by

$$Z_{i\parallel}{}^{(n)} = \frac{Z_{i\parallel}{}^{(n+1)}Cos\alpha^{(n+1)} - jZ^{(n)}Cos\alpha^{(n)}\tan\left(c^{(n)}d^{(n)}\right)}{Z^{(n)}Cos\alpha^{(n)} - jZ_{i\parallel}{}^{(n+1)}Cos\alpha^{(n+1)}\tan\left(c^{(n)}d^{(n)}\right)}Z^{(n)} \quad (4a)$$

$$Z_{i\perp}{}^{(n)} = \frac{Z_{i\perp}{}^{(n+1)}Cos\alpha^{(n)} - jZ^{(n)}Cos\alpha^{(n+1)}\tan\left(c^{(n)}d^{(n)}\right)}{Z^{(n)}Cos\alpha^{(n+1)} - jZ_{i\perp}{}^{(n+1)}Cos\alpha^{(n)}\tan\left(c^{(n)}d^{(n)}\right)}Z^{(n)} \quad (4b)$$

where $Z^{(n)}$ and $k^{(n)}$ stand for the impedance and wave no. of nth layer, $c^{(n)} = k^{(n)}$ Cos $\alpha^{(n)}$. If n is equal to N, $Z^{(N)} = Z_{i\parallel}{}^{(N)} = Z_{i\perp}{}^{(N)}$.

The wave absorbability of LHM absorbers is expressed employing the concept of reflection coefficient (r), the unit of which is decibel

$$r = 20\log\left(|R|\right) \quad (5)$$

It is a negative decibel. Bigger the absolute value of r is, better the wave absorbability of absorber. Therefore, to get the stealthy object one has to get the higher value of r in desired frequency region.

4. APPLICATION OF METAMATERIALS IN ELECTROMAGNETIC WAVE ABSORBERS

The experimental and theoretical advances in artificial metamaterials have offered scientists potent ways of tailoring the properties of electromagnetic waves. Metamaterials have manifested several exciting effects and devices, such as negative refraction, electromagnetic cloaking, super-resolution imaging, electro-magnetic concentrators and light trapping, in which the required constitutive parameters could be fulfilled by periodic/non-periodic arrays of electric or magnetic resonant/non-resonant structures.

The concept of simultaneous negative permittivity and permeability was postulated by Veselago in 1968 but it came into existence in 2000 when Smith[2], *et al.* have demonstrated a composite medium based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires that exhibits a frequency region in the microwave regime with simultaneously negative values of effective permittivity and permeability. Immediately after the demonstration of concept, a new approach to the design of electromagnetic wave absorbing structures has been proposed, in which the paths of electromagnetic waves are controlled within a material by introducing a prescribed spatial variation in the constitutive parameters[7]. The technique for determining this variation is based on coordinate transformations and electromagnetic cloaking is based on the same concept and it was first time experimentally demonstrated by Schurig[8], *et al.* The design process for the cloak involves a coordinate transformation that squeezes space from a volume into a shell surrounding the concealment volume. Maxwell's equations are form-invariant to coordinate transformations, so that only the components of the permittivity tensor and the permeability tensor are affected by the transformation, becoming both spatially varying and anisotropic. By implementing these complex material properties, the concealed volume plus the cloak appear to have the properties of free space when viewed externally. The cloak thus neither scatters waves nor imparts a shadow in the transmitted field and the same is explained by Fig 3. A cloaking structure with ten cylinders having square rings of variable dimensions as unit element is shown in Fig. 3 (a) and unit element with various design parameters is shown in Fig 3(b). Details of the design parameteres for unit element of each cylinder are given by Schurig[8], *et al.* Figures 3(c) and 3(d) describes the snapshots of time dependent steady-state electric field patterns with stream lines (black lines) indicating the direction of power flow, i.e. the Poynting vector. The cloak lies in the annular region between the black circles and surrounds a conducting copper cylinder at the inner radius. The fields shown are (C) experimental measurements of the bare conducting cylinder and (D) the experimental measurement of the cloaked conducting cylinder. Thus form the snapshot (D) it is clear that there are no scattered or transmitted power flow lines due to cloaked cylinder hence the concept of cloaking is experimentally proved at spot frequency. Due to its spot frequency response this technique is useful in narrowband

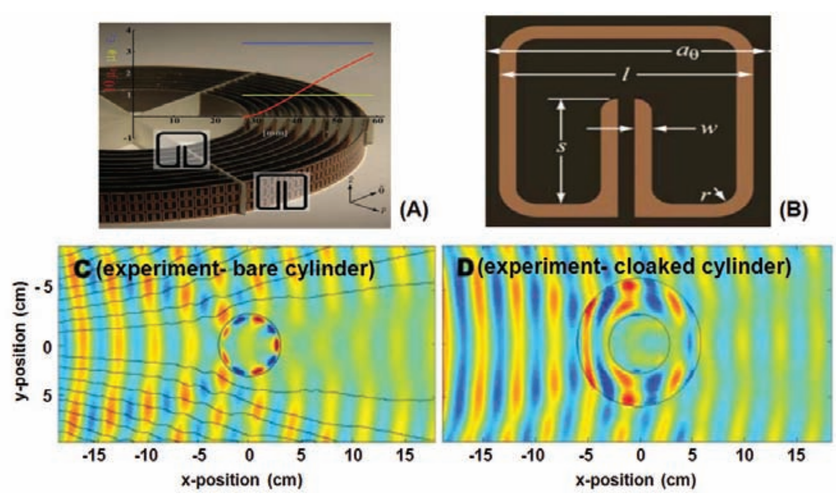


Figure 3. First experimental demonstration of cloaking at 8.5 GHz[8].

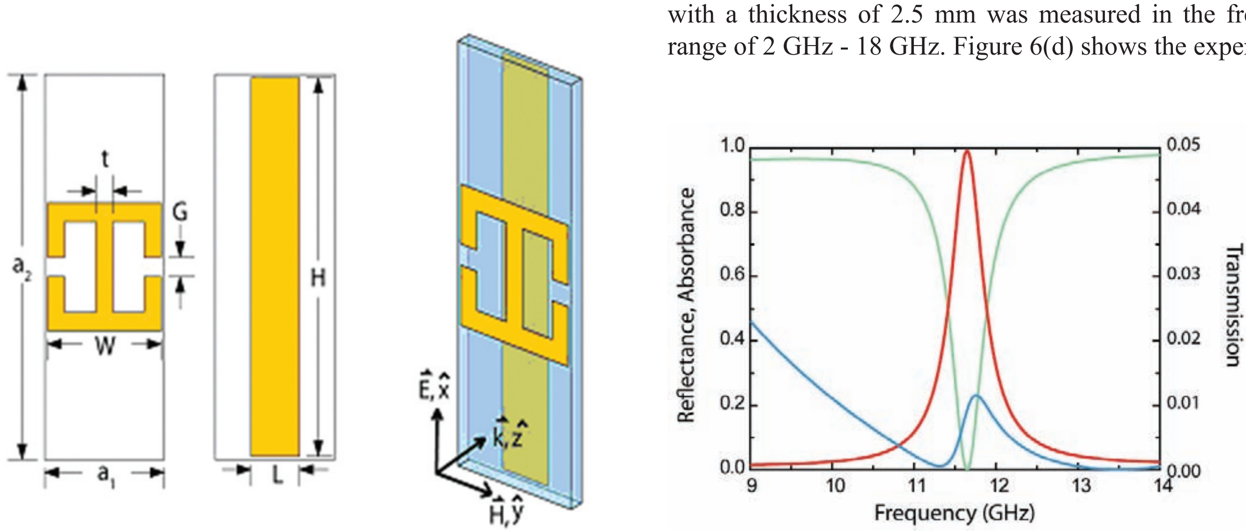
detectors such as bolometers.

Under the stealth applications, electromagnetic wave absorption is desired in broader bandwidth rather than spot frequency. Absorption bandwidth is usually defined in terms of full-width at half-maximum (FWHM) means the frequency band in which at least half of the peak absorption is achieved. To get the large bandwidth, Padilla's group demonstrated the perfect metamaterials absorber by utilizing the high imaginary part of the metamaterials index of refraction[9]. They utilized the lossy nature of metamaterials and achieved a thin absorber with a $\lambda/2.2$ unit cell dimension. A single unit cell of the absorber consisted of two distinct metallic elements as shown in Figs. 4(a) and 4(b) are considered. Electric coupling was supplied by the electric ring resonator (ERR), shown in Fig. 4(a). This element consisted of two standard split ring resonators connected by the inductive ring parallel to the split-wire. This design was used instead of a conventional split-wire design because of the limitations of straight wire media. Effective unit element is considered as shown in Fig. 4(c) in which both metallic components are separated by a dielectric spacer with axes indicating the direction of wave propagation. Figure 4(d) shows the simulation results for the proposed structure in which reflectance, absorbance and transmission are shown by green, red, and blue colours respectively. Simulated result shows that absorption is near unity (99%) at 11.65 GHz with a FWHM of 4 per cent and it has been concluded that by such technique nearly perfect absorption of electromagnetic wave is possible in narrow bandwidth.

From the above studies it was observed that operation of ordinary metamaterials is confined within a narrow spectral range, since dispersive resonances are exploited to control the permittivity and permeability of the structure. This comes to a major hurdle for stealth applications that demand broadband operation[10]. An enhanced bandwidth absorber based on double resonance has been proposed which has several crucial advantages[11]. The proposed metamaterials absorber consists of two conductive layers with a single substrate between them. The top layer has a dual electric resonator (DER), as shown in Fig. 5(a). The bottom layer has a ground plate without patterning as shown in Fig. 5(b) and complete fabricated structure is shown in Fig. 5(c). The main benefit of the complete ground plate on the bottom layer is zero transmission. However, in this configuration, the reflection cannot be perfect owing to the back-reflected wave from the ground plate, despite perfect impedance matching to free space. Therefore, a thick substrate is required to compensate for the increasing back-reflected wave because losses in the absorber are mainly from the dielectric substrate. The DER consists of a three-finger interdigital capacitor pattern to manipulate the electric response and increase the coupling losses so that the transmitted wave can be reduced. Owing to high coupling losses from the interdigital capacitors, the substrate thickness can be reduced to a thickness of about 0.02 λ. The DER is also designed as a hexagonal shape that is six-fold rotationally-symmetric about the propagation axis; hence, this absorber is polarization-insensitive. As a result, the proposed absorber has got double resonance with two distinct absorption peaks at 9.75 GHz and 10.3 GHz with 98 per cent absorption for different polarizations as shown in Fig. 5(d). Thus, the absorber exhibits a full-width at half-maximum (FWHM) of 11 per cent at 10 GHz while previously reported FWHM was 4 per cent.

Capabilities of metamaterials in electromagnetic absorbers have also been evaluated by the researchers of conventional materials. A group from Hunan University has demonstrated a scheme to enhance and tune absorption properties of conventional microwave absorbing materials by metamaterials[12]. They have proposed a combined metamaterials absorbing material, which is constructed by covering a single layer of metamaterials on the surface of a conventional absorbing material. To demonstrate the scheme, they have first fabricated a printed circuit board with split ring resonators (SRR) on one side and copper wires on the other. Then carbonyl iron powder coating (CIPC) was chosen as the absorbing material. Finally, the metamaterials layer was covered on the surface with CIPC to produce a combined absorbing structure, as shown in Fig. 6.

To see the effect of CIPC, the reflection loss of CIPC with a thickness of 2.5 mm was measured in the frequency range of 2 GHz - 18 GHz. Figure 6(d) shows the experimental



(a) (b) (c) (d)

Figure 4. (a) Electric resonator and (b) cut wire components of unit element (c) unit element with dielectric spacer and direction of wave propagation, (d) simulated pattern for reflectance, absorbance and transmission[9].

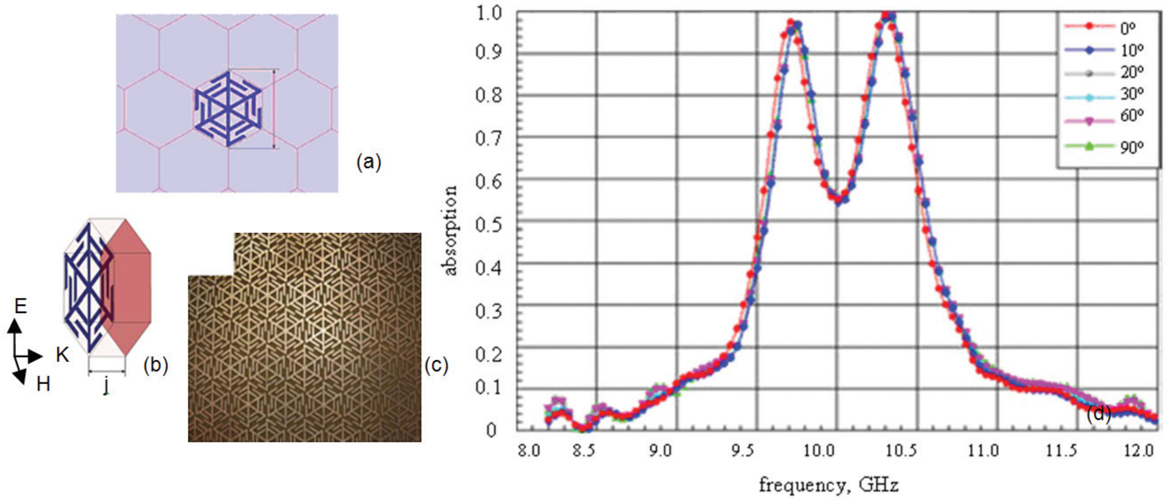


Figure 5. Bandwidth enhanced double resonance metamaterial absorber[11].

and simulated reflection loss of CIPC. Both results agree very well over almost whole frequency range studied and show that the microwave absorption peaks at approximately 6 GHz. The simulated maximum RL is slightly larger than the experimental one probably due to the tolerance in the fabrication and assembly. The microwave absorption property of metamaterials layer is indicated in Fig. 6(e). The electric field *E* and the magnetic field *H* are parallel to copper wires and SRR plane, respectively, and the wave vector *k* is parallel to the SRR axis. The simulated and experimental results of metamaterials are all close to zero, illuminating that the metamaterials layer does not absorb microwave in the frequency range of 2 GHz - 18 GHz in this case. After that the microwave absorption property of the combined structure was evaluated. Figure 6(f) shows the influence of metamaterials layer on microwave absorption property of CIPC for incident waves with the electric field *E* normal to copper wires. The simulated reflection loss of the combined structure agrees well with the experimental one, but both are close to that of CIPC, suggesting that the metamaterials layer does not increase the reflection loss of CIPC significantly in this case. Figure 6(g) illustrates the results when the electric field *E* is parallel to copper wires. The overall qualitative agreement between experimental and simulated results is good; the remaining discrepancies are likely due to fabrication tolerances in the experiment. A notable increase in reflection loss from -14 dB to -20 dB is observed by using a metamaterials layer. In addition, the frequency region in which the maximum reflection loss is less than -10 dB has been shifted to a significant lower frequency, from 5 GHz - 7 GHz to 4.2 GHz - 6.2 GHz. Shifting of reflection loss towards lower frequency was hugely appreciated because development of absorbers for lower frequency region is comparatively challenging.

All the above mentioned techniques were developed mainly at the microwave frequencies but researchers have attempted for higher frequencies until the unit cell dimension and metal skin depth become comparable. On the same concept

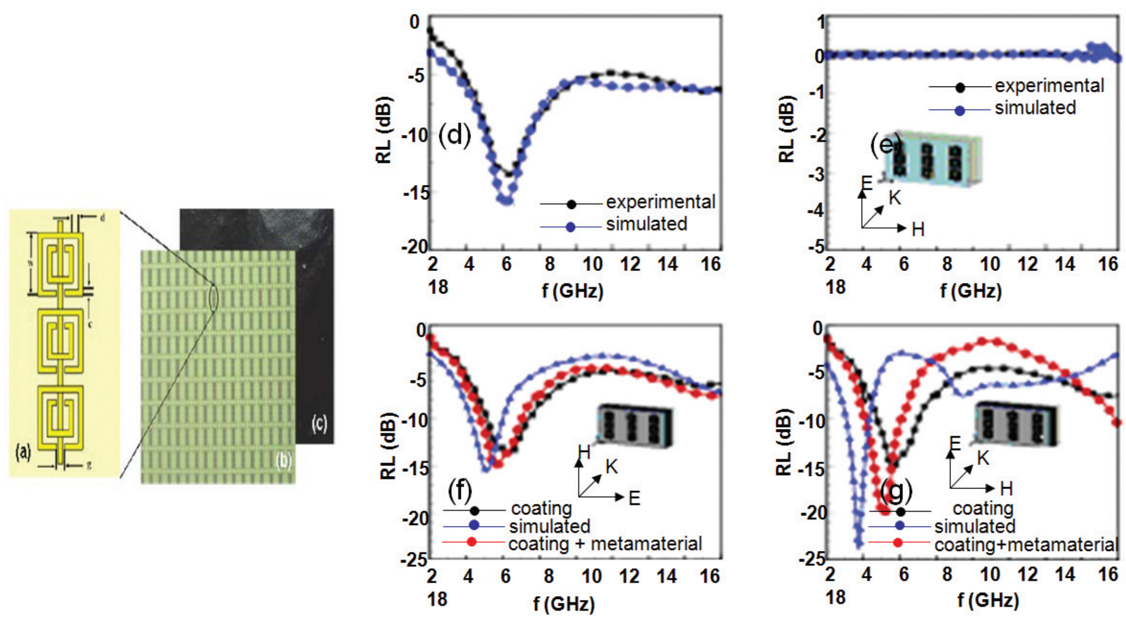
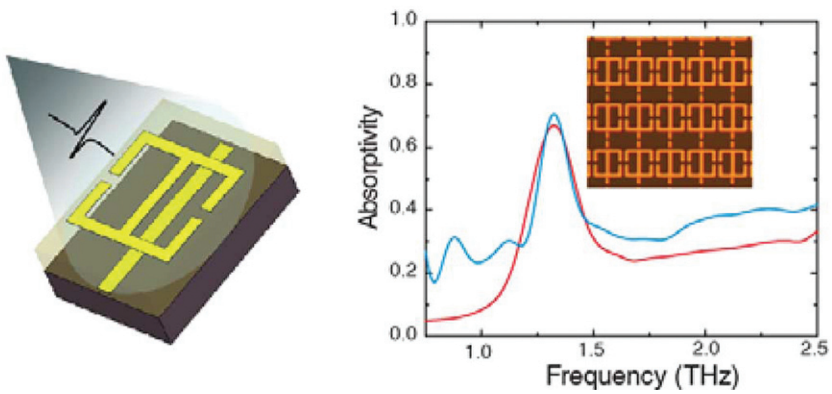


Figure 6. Unit element of metamaterial (a) for enhancing and tuning the microwave absorption by covering a single metamaterial layer (b) on CIPC (c) and observed results[12].

Tao[13], *et al.* designed the absorbers for terahertz frequency region. Unit element for the structure has been shown in Fig. 7(a). Proposed design consists of a bilayer unit element which allows maximization of the absorption through independent tuning of the electrical permittivity and magnetic permeability. On the basis of proposed design, they have demonstrated a first generation terahertz metamaterials absorber which achieves a resonant absorptivity of 70 per cent at 1.3 THz as shown in Fig. 7(b) where red plot shows simulated data and blue shows experimental results. Thickness of the metamaterials is 6 µm which corresponds to a power absorption coefficient of 2000 cm^{-1} which is significant at THz frequencies. The strong absorption coefficient makes this low volume structure a promising candidate for the realization of enhanced, spectrally selective THz absorbers. This work has opened the new field of counter measures of RCS technology because currently lot of research activities are going on RCS at THz frequencies where estimation of RCS for bigger objects is precisely possible using scale model analysis.

Due to the increasing demand of THz absorbers in RCS applications, study of absorption at THz has been extended to a polarization insensitive design[14,15]. Tao, *et. al.* have reported a compact metamaterials absorber consists of two metallic layers separated by a dielectric spacer. The top layer consists of an array of SRR which is primarily responsible for determining permittivity, while the bottom metallic layer is designed such that the incident magnetic field drives circulating currents between the two layers. Figure 8 presents such an optimized design which was fabricated and tested. The top layer (Fig. 8(a)) consists of an array of 200-nm-thick gold electrically resonant SRRs. A dielectric spacer layer of 8 µm thick separates this top layer from the bottom metallic layer. The bottom metallic layer is a continuous 200-nm-thick gold film. As Fig. 8(b) shows, there is a second 8 µm thick dielectric layer which provides mechanical support but, being behind the continuous gold film, does not contribute to the electromagnetic response. Figure 8(c) shows a photograph of a portion of the fabricated structure. The simulated absorption as a function of frequency for the fabricated structure is presented in Fig. 8 for TE (Fig. 8(d)) and TM (Fig. 8(e)) radiation at various angles of incidence. For the TE case, at normal incidence a peak absorption of 0.999 is obtained. With increasing angle of incidence, the absorption remains quite large and is at 0.89 at 50°. Beyond this there is a monotonic decrease in the absorption as the incident magnetic field can no longer efficiently drive circulating currents between the two metallic layers. There is also a slight frequency shift of ~30 GHz from 0° to 80°. For the case of TM radiation shown in Fig. 8(e), the absorption at normal incidence is 0.999 and remains greater than 0.99 for all angles of incidence. In this case, the magnetic field can efficiently drive the circulating currents at all



(a) (b)

Figure 7. Metamaterial based absorbers for terahertz frequency region[13].

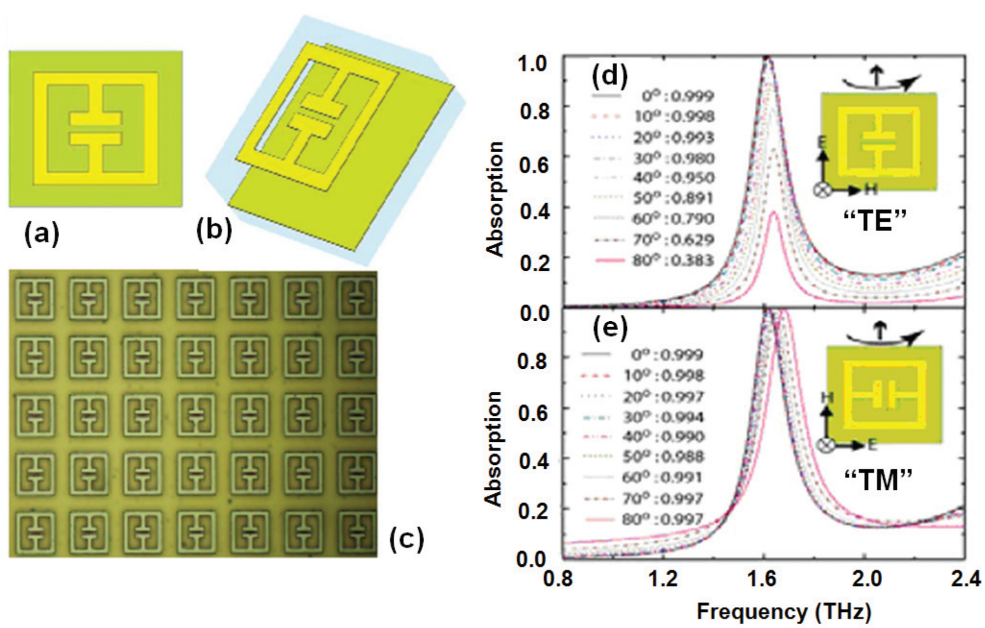


Figure 8. Flexible wide angle THz absorber and numerical calculations for high absorption over a wide range of angles of incidence for both TE and TM radiation[14].

angles of incidence which is important to maintain impedance matching. The frequency shift for TM radiation is ~80 GHz from 0° to 80°. As these simulations reveal, this metamaterials absorber operates quite well for both TE and TM radiation over a large range of angles of incidence. The absorber design is on a highly flexible polyimide substrate, which enables its use in non-planar applications. Therefore, such absorbers are pretty useful in practical situations of THz stealth technology where incoming signal may have huge variation in its charactertics.

In all the above mentioned studies various kind of structures with dielectric spacers or magnetic materials have been tried to achieve the perfect absorption. Up to certain extent perfection is accomplished but large absorption bandwidth is still an issue. To achieve the same, we have studied a multilayer structure of polymeric and chiral materials in the THz frequency region and the reflection loss with frequency has been measured for normal incidence[16]. Results obtained are shown in Fig. 9.

After the optimization process, four multilayer structures (A23, A47, A 128 and PANI-3) using different combinations and compositions of materials have been designed and fabricated and shown Fig. 9(a). Measured results (Fig. 9(b)) indicates that in general all the samples show 10 dB - 20 dB reflection loss in lower and higher side of measurement spectrum, whereas very high reflection loss, i.e., 20 dB - 30 dB (more than 99 per cent absorption of normal incident power) was observed between 1 THz and 2 THz, which is highly demanding feature in the development of any kind of absorbers for electromagnetic radiations.

Thus with the help of such structures bandwidth issue can be handled but in the absence of artificial structures/ metamaterials tailoring of electromagnetic properties is not possible. Therefore, authors further propose the study multilayer structures of polymeric and chiral materials along with printed periodic metallic patterns on the surface of each layer. The combination of highly absorbing polymeric materials and metamaterials may offer better absorptivity, large bandwidth and tailoring of electromagnetic response.

5. SUMMARY

The utilization and implementation of metamaterials as absorbers at Microwave and THz frequencies holds great promise. Metamaterials have attracted enormous attention and intensive research efforts, and a number of practical metamaterials based absorbers have been developed. Though most metamaterial absorbers operate over a narrow spectral band due to their resonant nature, efforts have been put in making absorbers with frequency tunability and multiple/ broadband functionality, which are favored for stealth applications. Based on the existing work, a novel approach for development of better electromagnetic wave absorbers has been put forward.

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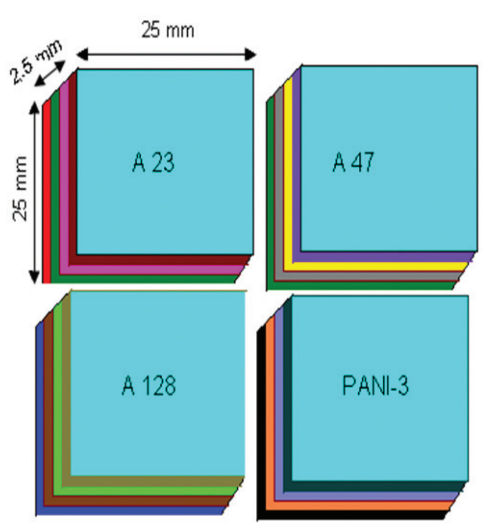
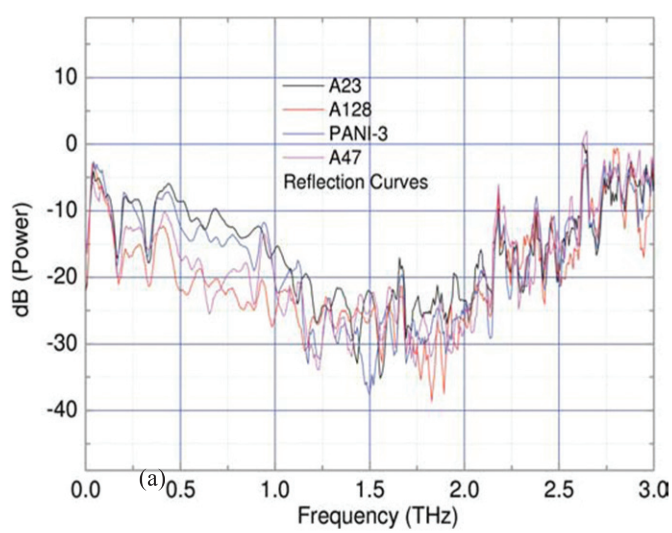


(a)



(b)

Figure 9. Schematic of fabricated structures (a) reflection loss measurements and (b) polymeric coating in THz region[16].

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