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Metamaterial Inspired Radar Absorbers: Emergence, Trends and Challenges

Anusha Eldo[1] and Balamati Choudhury[2]

Abstract The advances in metamaterial science and technology have raised the expectations of camouflage or stealth researchers to one order higher in terms of absorption characteristics. As metamaterial inspired radar absorbing structures are proving themselves as a good candidate with near unity absorption, feasibility towards hardware realization is necessary. Hence an extensive literature survey of metamaterial inspired radar absorbing structure has been carried out and reported in this paper along with the challenges and material issues. The various types of metamaterial structures that can be used as absorber have been provided along with simulation figures. To make the review more useful, graphene and carbon nanotube (CNT) based radar absorbing structures are also included along with their simulation and fabrication techniques.

Keywords: Metamaterial, radar absorbers, graphene, CNT, fishnet structures

1 Introduction

Artificially engineered materials has been a centre of attraction in the electromagnetic (EM) research and are coming up as an attractive solution to the performance constraints for the applications such as high performance antennas, super lenses [Fang *et al*. (2005)], radar absorbing structures [Choudhury *et al*. (2013*a*)], frequency selective surfaces and radomes [Shiv Narayan *et al*. (2012)]. Engineered materials made of designed inclusions, which are able to exhibit unique and exotic electromagnetic properties not inherent naturally in the individual constituent components and is the composition of inexpensive materials such as metallic inclusions and standard dielectrics. Further the applications of artificial material engineering became more popular with the introduction of artificial material called metamaterial, which having electromagnetic field properties not readily available in nature. With the framework of metamaterials, a considerable technological advancement for stealth platform for military applications has attracted a great interest currently.

Stealth or low observable technology is a comprehensive technique for reducing the probability of warhead systems such as aircrafts and warships from being explored by the enemy's diverse radar capabilities, in order to enhance the mission completion capability in the hostile terrain. The use of radar absorbing materials/structure is one of the solutions for low observable platform. Therefore, the techniques to combat these

[1] CSIR-NAL, Bangalore, India

[2] CSIR-NAL, Bangalore, India

challenges using artificially engineered materials called metamaterials are explored in this paper.

In this paper, an extensive literature survey has been carried out and reported along with the challenges in various aspects of design, bulk fabrication, measurement etc. The various metamaterial based radar absorbing structures like split ring resonators, fishnet structures, cut wire pairs, graphene based structures, CNT based structures, and composite structures, etc. are discussed elaborately along with the possibility towards design and development of flexible radar absorbing structure. Some of the high performance techniques to achieve broadband absorption over wide angle of incidence, polarization independent absorbers and absorption at terahertz frequency are also mentioned in this paper.

2 Challenges in Metamaterial Radar Absorber

Metamaterials are engineered to interact with electromagnetic waves and light waves in ways that natural materials cannot. They have the potential to be used in exciting applications such as invisibility cloaks [Choudhury *et al.* (2013)], radar absorbers, high resolution lenses, efficient and compact antennas etc. The various challenges of metamaterial as radar absorber are discussed in this section.

2.1 Design Issues and Fabrication Challenges

The characteristics of any metamaterial structure depend on the structural parameters and material properties of the constituent materials. The design of metamaterial structure has become a challenging task, due to lack of mathematical formulations that relates the constituent structural and material parameters with scattering characteristics and frequency of operation. Hence most of the metamaterial designs use numerical methods such as method of moment (MoM), finite difference time domain (FDTD), finite element method (FEM) etc.

It has been challenging to fabricate metamaterials that are electrically very large and non-planar which is the foremost requirement in stealth platform. Most of the microwave and optical metamaterials consist of tiny repeated metallic structures. When EM wave of particular frequency falls on them, it establishes oscillating fields inside each structure. These fields can resonate with each other and there by produce collective behavior. As the frequency of operation increases, the feature size gradually reduces and according to the design, fabrication also becomes quite difficult. Similarly fishnet metamaterial structures suitable for electrically large structures have several vertically stacked repeated units spread over much larger lateral dimensions. These fishnet structures can be fabricated by carefully patterning individual films on top of each other. This multilayer process is difficult as it requires careful alignment of the films. Also maintaining the thickness is quite difficult practically. Another challenge encountered is the design and fabrication of conformal metamaterial structures, which have extensive applications in stealth and cloaking applications. The design of conformal metamaterial structures is gaining momentum as the military aviation is moving towards the fifth generation combat structures.

Design and fabrication of optical metamaterials are more challenging as compared to microwave applications. At optical frequencies, metals no longer behave as perfect electrical conductors and also the resistive and dielectric losses become much more significant and a frequency value is eventually reached, at which the energy of the oscillating excited electrons becomes comparable to the electric field. During this period the response of metals is known as plasmonic. These effects come into play while designing metamaterials for optical applications.

2.2 Material Challenges

For applications such as stealth platform for aerospace domain, selecting the constituent materials for designing metamaterial structure is quite challenging. Since the various physical, chemical, and thermal properties of the materials should meet the requirements. As metamaterials are EM patterns of metallic strips on dielectric materials, the property of the dielectric materials along with the conductivity of metallic patterns play an important role. At some frequency of operation the metallic patterns made up of gold provides good absorption e.g. at terahertz frequency gold patterned metamaterial based absorbers provides near unity absorption than copper patterned [Choudhury *et al*. (2013*b*)]. These properties increase the cost of the system.

2.3 Measurement Challenges

Measurement of electrical properties of the metamaterial structures is always a daunting task as these materials are mostly anisotropic in nature and also constitute metallic inclusions or metallic structures embedded to it. Further these structures are resonant in nature; hence requires a measurement set up. Figure 1 shows the typical measurement setup of frequency selective surfaces available in CSIR-NAL, Bangalore.

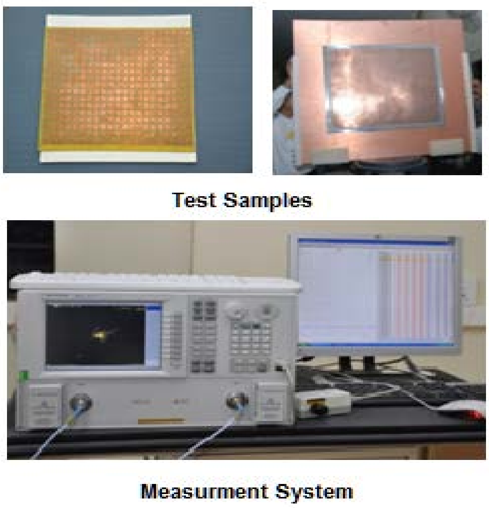

Figure 1: Typical RCS measurement setup of metamaterial structures

2.4 Need for Broadband Absorbers Structures

The developments in broadband radar systems are putting up a challenge in the stealth platform which imposes a necessary requirement in the radar cross section reduction technology to include broad-banding aspects into the EM design. Conventional broadband radar absorbers *viz. Jaumann absorbers or circuit analog absorbers* are multilayer in nature [Vinoy and Jha, (1996)] and the performance decreases as one decrease the number of layer. As the modern absorber design requires less weight and high performance over two to three bands it is very difficult for EM designer to come up with these designs. This paper will be focusing on some of these issues and the suitability of metamaterials in such applications.

3 Metamaterial Radar Absorber

The concept of metamaterial was introduced by Vaselago in 1968, but the unique electromagnetic features such negative refractive index, negative phase velocity, negative permeability/permittivity are synthesized by Pendry *et al.* in 1999 as a periodic pattern of sub wavelength resonator such as split ring resonator (SRR's) and metallic rods. This leads to the synthesis of electromagnetic devices such as thin radar absorbers, high gain antenna arrays, cloaking devices, and perfect lenses. A structure which absorbs all the incident electromagnetic radiation without any reflection or transmission is known to be an ideal absorber. The key parameters that affect the absorption performance are material properties such as effective permeability and permittivity, morphology, and thickness of structure. This section explores the trends in metamaterial absorber structure design and applications to various fields.

3.1 Metamaterial Resonating Structures

Resonant absorbing structures rely on materials or structures which interact with incident wave in resonant way at a particular frequency, so band width of absorption is very narrow. Generally resonant absorber consists of multiple layers with spacing of quarter wavelength of operation. As the load impedance match to free space impedance, the reflection became zero and with the addition of loss high absorption is achieved. The classification of metamaterial absorber resonating structures is shown in Figure 2 and is detailed in this section.

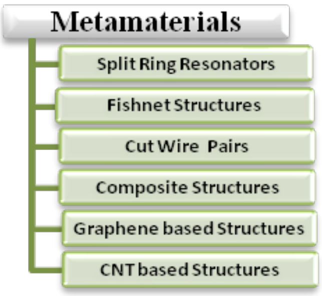

Figure 2: Classification of Metamaterials

3.1.1 Split Ring Resonator

In order to respond to the magnetic component of the electromagnetic wave, the typically used element is split ring resonator (SRRs) and this 'magnetic atom' was introduced by Pendry in 1999. According to Padilla *et al*. (2006), in simple terms SRR can be considered as an LC resonator. An EM wave with magnetic field perpendicular to plane of SRR induces circulating currents as in Faraday's law. This circulating current results charge formation across the split gap of SRR, so the energy is stored as capacitance. Hence the SRR is considered to be as simple LC circuit with a resonant frequency. Above the resonant frequency even though external magnetic field is increased, the current can no longer keep up and gradually begin to lag, which results in an negative response or out of phase.

Smith *et al.* (2000) fabricated the negative index (NI) material by using the metamaterial structures. The structure consists of combination of a wire structure with negative permittivity and a split ring resonator structure with negative permeability for the same frequency band, resulting negative refraction. The same negative refraction was demonstrated and confirmed through Snell's law experiment by using metamaterial wedge in prism shape [Shelby *et al.* (2001)]. The incident microwave radiation on the surface of prism was refracted to the opposite side of normal to the surface, hence shows the negative refraction.

The negative refractive index property of metamaterial based structures leads to the idea of super lenses. Pendry *et al.* (2000) predicted that the focus produced by a flat slab of negative refractive index material exceeds the diffraction limit. So it is possible to recover the exponentially decaying evanescent waves produced by the source through imaging by slab. EM radiations from all sources consist of both steady component and decaying component. The exponentially decaying components cannot be recovered using positive index lenses, since this near field components conveys the finest details of object, positive refractive index material limits the resolution of the image formed.

Split ring resonators are widely used as metamaterial unit cells towards EM wave absorber designs because of their exotic properties. Jain *et al.* (2006) explained the fabrication of electromagnetic absorbers, radio frequency lenses, and phantom materials by using the artificial dielectrics. They also developed the formulae for permittivity estimation of artificial dielectrics. The disadvantage of split ring resonator based absorbers is of narrow bandwidth. In order to overcome this challenge, Pang *et al*. (2012) proposed a broadband and ultrathin high impedance absorber on a metamaterial substrate for microwave frequencies. The proposed structure consists of split ring resonators (SRRs) embedded vertically into dielectric slab. This structure gives an expanded bandwidth of absorption for less than -10 dB. The field distribution characteristics showed that the enhanced characteristics related to the LC resonance. The results demonstrate that proper design and optimization of metamaterial structures make them suitable for broadband radar absorbers.

Further, the applications of absorbers in mid infrared region are also affected by the narrow bandwidth absorption characteristics of split ring resonators. One of the aspects of broad banding metamaterial inspired absorbing structures in mid infrared regime was demonstrated by Ma *et al*. (2013). In the proposed structure, two or four cross resonators made of gold with varying sizes are multiplexed on SiO2 layer with a gold layer at the bottom. The Q factor of cross resonator absorbers decreased as the number of cross resonators increases, hence bandwidth of absorption improved. For an absorber with four multiplexed cross resonators the absorption bandwidth covers the entire mid infrared region with more than 50% absorbance. The proposed structure found applications in IR detection and energy harvesting.

Earlier, split ring resonator along with cut wire metamaterial structure is the primarily used one in radar absorbing applications, whereby perfect absorption was achieved through controlling the magnetic and electric resonance independently. Later the type of metamaterial structures motivated a new wave of research, for instance fishnet structures, photonic band gap (PBG) based structures and recently the inclusion of graphene and CNT based structures.

3.1.2 Fishnet Structures

Fishnet structures are one of the widely explored metamaterial structures for optical applications. Alici *et al.* (2008) investigated numerically and experimentally, the existence of negative refraction in planar metamaterials such as cut wire pairs and fishnet structure at 21 GHz. For characterization through effective medium theory, the planar metamaterial is theoretically modeled as LC circuit. They experimentally proved the negative refractive index for fishnet structure in microwave and optical frequencies. Even though the fishnet structures exhibit negative material characteristics and are suitable for EM absorber applications, its fabrication is quite challenging. Dutta *et al.* (2010) demonstrated the fabrication of metamaterial fishnet structures for IR wavelength. The proposed structure consists of pair of metallic thin layers with periodic rectangular perforations separated by a layer of dielectric layer. The proposed structure is shown in Figure 3.

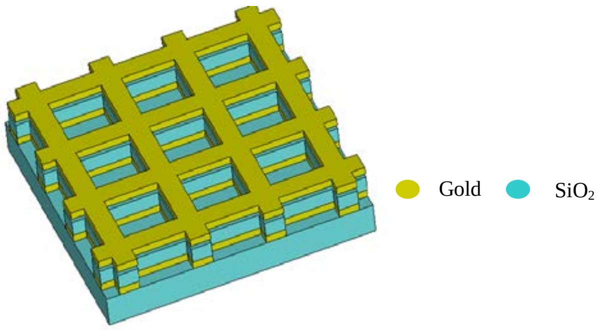

Figure 3: Schematic of fishnet metamaterial structure

The fabrication processes detailed are compatible with CMOS technology presently used. So the proposed technique is suitable for bulk fabrication.

3.2 Graphene and CNT Based Structures

The incorporation of thin sheets of carbon viz. graphene, CNT etc. into metamaterial structures is a relatively new concept. The key attraction of this concept is the thickness reduction and tuning of absorption characteristics. Iorsh *et al.* (2012) suggested a new class of hyperbolic metamaterial structure by using multilayer graphene structure. The permittivity tensor calculation for the effective medium has also been reported towards absorption analysis of these structures.

The suitability of graphene and multi-walled CNT (MWCNT) as a potential candidate for radar absorbing material was experimentally proved by Bhattacharya *et al.* (2012). The developed RAM has a sample thickness of 2 mm and 10% loading. For morphological study transmission electron microscopy (TEM) and field emission scanning electron microscopy (FESEM) were used. The scattering parameters were measured using vector network analyzer in X band region. The experimental results showed that absorption capability of graphene is better than MWCNT.

The ability of graphene to absorb electromagnetic waves was analyzed theoretically by Kryuchkov *et al.* (2013). The power absorbed is calculated using Boltzmann kinetic equation and simulated the same in Monte Carlo simulation. They have shown that power absorbed is directly proportional to radiation amplitudes and is independent of electron gas statistics. Based on these concepts, several graphene based absorbing structures are introduced. He *et al.* (2013) proposed a graphene based anisotropic metamaterial structure. The introduced broadband absorber in terahertz frequency consists of a number of dielectric and graphene layers in frustum pyramids shape. The multilayered structure can be thought of as a homogeneous metamaterial with anisotropic permittivity and hyperbolic dispersion. On graphene layers surface plasmonic waves are excited and due to the squeezing effect at the tapered waveguide by the slow waves, the incident EM waves are absorbed.

The interaction between graphene and metal results some exotic response to incident EM wave. Zhao *et al.* (2013) presented the EM wave absorption property of Ferrite based nano composites coated with graphene. The interfacial electronic interaction of graphene and metal leads to some novel magnetic and electronic properties, resulting in excellent absorption performance in a wide microwave frequency range. For large area surfaces, the low density highly stable Fe/G acts as the ideal coating for potential applications. Further, the capability graphene and CNTs to absorb electrical component of EM wave was investigated by Das *et al*. (2013). They conducted their studies on four different samples, two of them with CNT and other two with graphene. Samples are tested at microwave X band (8 – 12 GHz). The reflection loss obtained for each samples is given by -14.8 dB by RAM-1 (CNT/ Fe O / Polyphosphazene), -23.4 dB by RAM-2 (Graphene/ Fe O / Polyphosphazene), -20.1 34 dB by RAM-3 (CNT/ FeO / BaHF/ Polyphosphazene) and -21.32dB by RAM-4 (CNT/FeO/FeSi/ Polyphosphazene).

One of the main advantages of graphene based absorbing structures is its frequency tuning capability over a wide range. Zhang *et al.* (2014) utilized graphene for designing tunable metamaterial radar absorber in terahertz frequency by taking advantage of its controllable sheet conductivity. The proposed unit cell structure comprises of metallic resonator in cross shape along with double layers of graphene sheets, as shown in Figure 4.

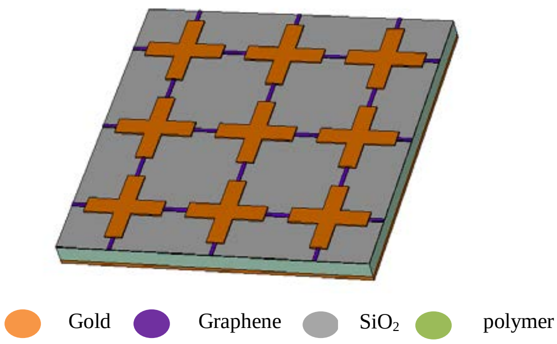

Figure 4: Structure of proposed graphene based metamaterial absorber

The tuning mechanism behind the proposed design was explained by exploring the transmission line equivalent model. By changing the bias voltage between the two layers of graphene the effective inductance can be controlled, hence tuning of absorption frequency is achieved. Graphene based tunable metamaterial radar absorbing structures has extensive applications because of their broad band characteristics with reduced thickness and easy tuning mechanism.

3.3 Plasmonic Structure

Plasmonic structures act as efficient absorbers due to excitation of photonic resonances and are found applications in photonic detection and solar energy harvesting. Cheng *et al*. (2012) studied a metallic disk broadband absorbing structure on SiO_2/Ag/Si substrate. By tailoring the ratio of size of disk to area of unit cell, the absorption can be improved. For both TE and TM polarization, the localized surface plasmon polariton (LSPP) mode was exhibited by the metallic disk. By altering the disk size, wide angle, high performance, dual band absorber independent of polarization was achieved. It found applications in sensors, photovoltaics, and camouflage due to its substantial flexibility.

Cui *et al.* (2012) demonstrated a plasmonic absorber for multiband operation based on transverse phase resonances. The T shape grooves in the conventional metallic surfaces create mode splitting of plasmonic waveguide cavity. Thus the new resonant modes result more than 90% absorption having wide angle characteristics.

3.4 Broadband absorbers

Radar absorber application always demands for broadband operation. As most of the metamaterial structures have narrowband of absorption, various techniques are developed for the concept of broad bandwidth. One of the common methods found in literature is the use of multiple resonating structures in single unit cell. It is the basic concept of incorporating the resonators with varying sizes, which resonate at near frequencies. If obtained absorption resonances in the absorption spectrum are close enough in frequency, they will result a broadband absorption. Figure 5 shows a unit cell consists of more than one structure with different dimensions exhibiting resonance at near frequencies and resulting wide bandwidth.

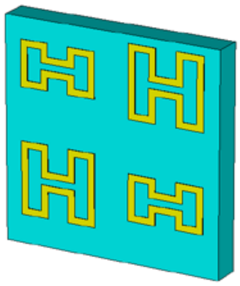

Figure 5: H shaped unit cell structure for broadband absorption.

Wakatsuchi *et al.* (2010) presented a broadband metamaterial absorber for arbitrary polarization by using lossy cut wire pair metamaterials. The lossy cut wire pairs with different lengths are combined as a periodic unit and are placed near to PEC. The simulations are performed by using transmission line modeling. The main advantages of lossy cut wires as compared to other metamaterial structures are simplicity of structure and there is no requirement of an extra metal component to yield a negative refractive index (NRI). The paired cut wire structure exhibit both electric resonance and magnetic resonance, also it works for both polarizations. The structure gives an absorption peak of 0.76 at 27 GHz.

One of the simple broadband radar absorbing structures at microwave frequencies is multi ring structure [Liu *et al*. (2012)]. The designed structure consists of circular metallic patches and PEC ground plane and dielectric spacer. For broadband resonance characteristics a number of metallic patches adjacent resonant peaks are used. The proposed structure is shown in Figure 6. Experimental results showed that the structure has an absorption bandwidth of 2.8 GHz and relative full width half maximum (FWHM) bandwidth of 25.3%.

The principle of multiple resonating structures in single unit cell is also applicable to plasmonic radar absorbing structures. Wu et al. (2012) introduced ultrathin broadband plasmonic absorber with unit cell consisting of subunits of different sizes with 100% absorption at adjacent frequencies. A theoretical model for each subunit was represented by series circuit model for predicting overall response. The circuit model is based on short propagation lengths of surface plasmons.

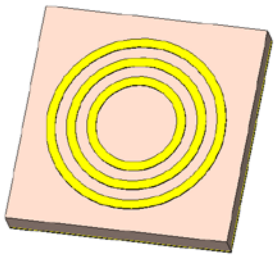

Figure 6: Multiple ring structure for broadband absorption

There is another possibility of stacking multiple layers with different size resonators, in which resonators share a common ground plane, but it is difficult to fabricate such structures. The multiple resonances can also be achieved through sectioning a single structure, which resonates at different frequencies. Grant *et al.* (2011) demonstrated design, simulation, fabrication and measurement of a broadband metamaterial absorber in terahertz frequency. The closely positioned resonant peaks of stacked metal insulator layers with different structural parameters made the absorption spectrum broader. For a bandwidth of 1.86 THz, the obtained absorption for the proposed structure was more than 60%. Also the FWHM obtained was about 48% and it found application in bolometric terahertz imaging.

The fractal geometry of unit cell also paves the way to broadband absorption. Sun *et al.* (2012) designed and fabricated a metamaterial with lossy frequency selective surfaces for broadband operation. The unit cell comprises of fractal square patch and crisscross coupled with each other and this interaction leads to improved bandwidth of absorption. The simulation and experiment result, the bandwidth with reflectivity below -10 dB is 6.6-18 GHz for 3 mm thick absorber. Due to symmetry in geometry, the absorption characteristics are independent of the polarization of incident radiation.

Nowadays the concept for realizing broadband absorption through introduction of lumped elements into metamaterial structure is gaining momentum. It is regarded as a promising method for achieving broad absorption spectrum. Yang *et al.* (2007) presented the design of a broadband absorber by using double square loops as unit cells. The introduced design contains lumped resistors of suitable value in all the four sides of the loop. These loops are printed on a dielectric substrate with a conducting or metallic back plate, in order to minimize the transmission. The design is simulated in HFSS and results showed that by using this structure 10 dB RCS reduction is achieved over a range of 8-18 GHz frequency with relative bandwidth of 77%.

Inclusion of active components in the unit cell for broadening the bandwidth is introduced by Xu *et al.* (2007). They put forward a metamaterial based absorbing structure, where both radar cross section (RCS) and transmission coefficients were electrically controlled. The proposed structure comprises of SRR's and metallic wire strips, and controllability is achieved through the inclusion of pin diodes inserted between the metallic wire strip arrays. The electronic control is provided by a master-slave mechanism through voltage control across diodes and the *on* or *off* state of pin diodes determines the RCS and transmission coefficients.

Yuan *et al.* (2014) designed and experimentally validated lumped element based metamaterial absorber for broadband absorption in the microwave frequency range. In this composite metamaterial absorber (CMMA), the EM wave energy is converted to electrical energy and subsequently consumed by lumped resistors. The designed CMMA has absorption characteristics insensitive to polarization and angle of incidence. The experimental results showed that CMMA yields below -10 dB in the frequency band from 2.85 to 5.31 GHz with relative bandwidth of 60.3 %.

3.5 Polarization Independent Absorbers

As radar absorbers are mainly used in stealth applications, the designed structures must be capable of absorbing EM wave incident on any angle and any polarization. The design of symmetric structures in the unit cells is the best way to achieve polarization independent absorbers. Dimitriadis *et al.* (2012) put forward a novel metamaterial absorber in the X band with enhanced band width and wide angle absorption characteristics independent of polarization. The structure consists of Circumscribed-Cross-Resonator (CCR) printed above a dielectric substrate with metallic back plate. Due to complete symmetry the absorption characteristics are independent of the polarization of incident wave. The simulation results showed an absorption peak of 96.4% at 9.82GHz and FWHM of 5.2 % near central frequency.

Bhattacharyya *et al.* (2013) proposed a metamaterial absorber with polarization independent characteristics and wide angle of incidence. The unit cell of the designed structure consists of ring resonator loops in square shape. The structure exhibits triple band absorption response with one band in X band and other two bands in C band. In X band the structure has a FWHM bandwidth of 940 MHz. Also the experimental results showed that the absorption is high upto an angle of incidence of 60^o.

3.6 Design of Flexible Structures

Modern stealth applications demands for design of flexible metamaterial structures for conformal applications. Cheng *et al.* (2012) studied a metallic disk broadband absorbing structure on SiO_2/Ag/Si substrate. By tailoring the ratio of size of disk to area of unit cell, the absorption can be improved. For both TE and TM polarization, the localized surface plasmon polariton (LSPP) mode was exhibited by the metallic disk. By altering the disk size, wide angle, high performance, dual band absorber independent of polarization was achieved. It found applications in sensors, photovoltaics, and camouflage due to its substantial flexibility.

Further, the concepts of broad banding techniques are included to the conformal structures. Campbell *et al.* (2013) proposed the design of dual concentric ring resonator on a flexible substrate and named as meta-films. The simulation results showed that the absorption characteristics are independent of oblique angle of incidence and polarization. The flexible structures with multiple resonance frequencies are feasible for conformal radar absorbing structure applications.

4 Metamaterial Absorber Structures at Terahertz Frequency

Most of the research on optical metamaterial structures has been at the theoretical stage. The mathematical characterization of nano-scale plasmonic effects and computer simulations of proposed design are carried out in this field. Physically realization of optical metamaterials is not done significantly, even though metamaterial technology is implemented successfully in microwave spectrum.

Moser *et al*. (2005) designed and fabricated a metamaterial structure based on a rod-split ring resonator by using micro-fabrication technique. The structure was simulated numerically and further verified using measurement technique called IR transmission spectroscopy. In the frequency range 1 to 1.27 THz, the designed structure behaved as metamaterial. The authors also proposed the technique called micro fabrication techniques for fabrication of structures for IR range frequency operation. Padilla *et al.* (2006) studied the characteristics of a planar array of SRRs with Gallium Arsenide (GaAs) as dielectric substrate. The proposed structure has an absorption bandwidth of 1.1 THz from 0.5 THz to 1.6 THz. They also studied the dynamic control over the metamaterial structure through impinging light on GaAs substrate and how the power of incident light affects the different absorption frequencies.

The concept of multiple resonance frequencies is extended to terahertz frequency regime also. Hand *et al.* (2008) designed and fabricated hybrid resonators exhibiting dual band resonances at 1.48 THz and 1.29 THz. They studied radiation analysis at THz frequency for 60 %, 90 %, and 100 %. The results shows that as manufacturing defect increases, the resonance degrades as impurity effects are more significant at terahertz frequencies.

Han *et al*. (2009) proposed close ring pair metamaterial structure for terahertz regime. The structure shows resonance at normal excitation, not during in plane excitation. The proposed structure was simulated and fabricated and extracted the material parameters at resonance frequency.

Sabah *et al*. (2009) investigated the evolution of design and applications of metamaterial structure for terahertz frequency regime. They designed a structure with two SRRs and a thin wire for broadband operation in the terahertz frequency with resonance at 4THz and 2.7 THz. This hybrid structure has a combined effect of two structures and at 3THz, structure results maximum negative refractive index. Further they [Sabah *et al*. (2011a)], [Sabah *et al.* (2011b)] introduced polarization independent dual-band fishnet metamaterial structure for applications in terahertz frequencies. Further Sabah *et al*. (2011c) explored the metamaterial multilayer structure. The structure with dielectric and chiral material together gives the optimum performances such as polarization rotation and spectral filter. The proposed structure can be used for coating, filtering, and in devices for polarization conversion in terahertz frequency.

Ortner *et al.* (2010) explained resonant characteristics of SRR and CSRR (complimentary SRRs) by using THz near-field microscopy and THz time domain spectroscopy. They verified that the characteristic response is due to the magnetic near field developed. From the observations, they developed THz-near-field imaging method, which facilitates spatially resolved measurements of phase, amplitude, electric field polarization etc. The simulations results are in conformity with the proposed theory and Babinet's principle. Further, the coupling between the SRRs in an array is explained by Wallauer *et al*. (2011) through THz near-field microscopy and THz far-field spectroscopy. In the coupled structure it was observed that a macroscopic dipole moment was developed from the fundamental LC resonance from individual SRRs.

Cheng *et al.* (2012) proposed a terahertz chiral metamaterial with U-shaped structure. The chiral configuration of metamaterial structure results negative refractive index. The structure shows strong optical activity upto an angle of 53^o and can be used as a polarizer.

In the terahertz frequency regime, the size of the unit cell structures is relatively small and fabrication became difficult. Fabrication of terahertz metamaterial structure using metallic rings was explained by Li *et al.* (2013). The fabricated structure exhibits isotropic dual band operation. The periodic repetitions of metallic rings possess negative permittivity for a frequency range of 652–780 GHz and 298–388 GHz. The measurements are carried out using time domain spectroscopy and the results are well agreed with the simulation results.

5 Conclusions

Metamaterial inspired radar absorbing structures have been explored extensively in this paper. The challenges in design, optimization and fabrication have been reported along with an analysis of suitability in stealth platform. Further, design simulations of various types of metamaterial structures along with graphene and carbon nanotube based absorbers are also provided so as to make the review more useful to the readers.

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