CHAPTER-I

INTRODUCTION TO META-STRUCTURE ABSORBER

1.1 INTRODUCTION

Meta-structure absorbers (MSAs) are engineered to uniquely amalgamate the sub-wavelength resonating periodic structure feature of metamaterial absorbers with the material properties of the resonating structures resulting in a broad absorption bandwidth [1-6]. Manipulation of shape and design of the resonating structure enables achievement of desired absorption characteristic, operational frequency bandwidth and polarization insensitivity. Resonators are usually made up of high lossy material while the substrate matrix are of low loss material jointly provide minimum resistance to the incident electromagnetic (EM) wave while entering the absorber and achieve sufficient attenuation on penetration. Figure 1.1 shows schematic of some of the MSA unit cells. The resonators are developed either as protruding structures shown in Figure 1.1(a)-(c) or within the substrate as planar-embedded structures as in Figure 1.1(d).

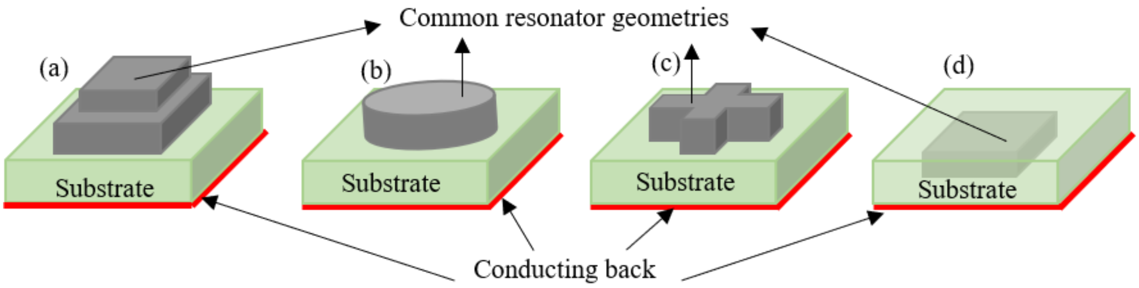

Figure 1.1 Schematic of MSA unit cells with protruded (a)cuboidal (stacked), (b) cylindrical, (c) cross shaped resonators and (d) planar-embedded cuboidal resonator.

In addition, physical properties of the resonator as well as the substrate material should be suitable to provide robustness and strength making it less prone to performance variation under different environmental conditions. CC/wax-based meta-structures are filled into 3D printed verowhite polymeric shells in reference [7] as protective cover to develop the absorber. Structures of different subwavelength dimensions are stacked to obtain ultrabroad-band with a thickness of ~ 11 mm. Additive manufacturing is also employed in [1], for developing a complete meta-structure absorber using graphite SLS. The resonators are stacked onto one another for achieving wide bandwidth absorption in the operating range 7.6-18 GHz. A similar approach is used to develop three layered meta-structure absorber using nylon/carbonyl iron SLS [8] operating in the range 8-18 GHz. The absorbers thus developed are, however, rigid.

A flexible embedded hierarchical meta-structure is demonstrated in [5, 9] using silicone rubber matrix wherein carbonyl iron (CI) and multiwall carbon nanotube (MWCNT) are infused in silicone to obtain a 5 mm thick absorber operating in S to Ka-bands. In another approach to develop lightweight MSAs, liquid resonators are incorporated in substrate. Periodic arrangement of water droplets has been used to obtain broadband absorption, owing to its high dielectric loss tangent ~ 0.5 [10-16]. Flexible water embedded single layered MSAs are demonstrated in X-band frequency range using hydrophobic silicone-rubber [2, 6, 17]. Although potential applicability of ionic liquids (ILs) in microwave absorption are reported back in 2008 [18], however, exploitation of ILs for developing MSAs is lately investigated as late as 2017 [19]. Methylimidazolium ionic liquid is enclosed in cylindrical shaped resonator arrays to achieve ultrawideband absorption [19, 20]. In lieu of IL, encapsulated aqueous electrolyte meta-structure based absorber had been reported in 2019, using aluminium chloride ($AlCl_3$) as a fluid filler for a periodic rectangular meta-structure absorber. A wide absorption bandwidth with 90% absorption throughout the X-band region is observed [21].

1.2 FORMULATION OF RESEARCH PROBLEM AND OBJECTIVES

Integration of microwave and electronic components into single platform in the past few years, a need is strongly felt for flexible absorbers that are lightweight, thin and broadband. Despite having a wide absorption bandwidth, resonators made of solid materials in MSAs can make the absorbers overall heavier and restrict its stretchability and flexibility, as evidenced from the literature [1,5,7-9]. Besides, extended usage and repeated bending can have detrimental effect on the absorber's performance by increasing the risk of fatigue and fractures in the constituent materials. On the other hand, liquid resonators [2,6,10-21] although lightweight, too have limited stretchability. Liquids also limit matrix material choices and show fabrication complexity.

The current research problem has been formulated to develop absorbers that could overcome the limitations of the existing meta-structure absorbers while incorporating their advantages. Consequently, the principal deliverables of a meta-structure absorber are sought to be–

- sufficiently flexible and unaffected by bending/stretching: for easy mounting on curved surfaces
- compact and lightweight preferably 2D layered structure: for use in compact devices and systems
- robust and inert to harsh environmental conditions
- wide absorption bandwidth at wide polarization angles
- easily fabricable, repairable/restorable and eco-friendly

Liquids have been immobilized using polymer matrix for developing gel-based stretchable electronics to facilitate handling [22-26]. Gels behave as a semi-solid with properties intermediate between solid and liquid. Most of the gels possess self-healing and good shape restoration ability/revertibility [27-29], which could be exploited for developing flexible absorbers.

In light of the aforementioned literatures and the requirements for current microwave technology, the objectives of the current work have been envisaged below:

I. Use gel as resonating structures in combination with pliable matrix to develop flexible meta-structure absorbers.
II. Enhance absorption bandwidth in the operational band by exploiting the lossy properties of gel and shape and size of the resonating element.
III. Symmetrical simple geometry incorporation for wide polarization angle absorption and easy fabrication.
IV. Thickness $\leq \lambda/10$ to get low profile MSAs with convenience of mounting.
V. Jacketing the resonators into environmentally inert sheath to get more robust structures.
VI. Evaluation of possible applications of the developed MSAs.

Radars in both military and civilian applications mostly use the X-band frequency (8.2-12.4 GHz) [30-41]. As a result, shielding has become crucial in the X-band frequencies to reduce electromagnetic interference (EMI) and radar cross section

(RCS). Hence, the proposed absorbers are developed and tested in the X-band, however, the designs are easily modifiable to any other anticipated microwave frequencies.

1.3 ABSORPTION MECHANISM OF A META-STRUCTURE ABSORBER

Material effectively absorbs impinging EM radiation when fundamentally two conditions are met -

1. Minimum resistance at the air-absorber interface to maximize penetration of the EM wave.
2. Maximum attenuation of the penetrated EM wave within the material.

Absorption is mathematically given by [42, 43]

$$A_\omega = 1 - R_\omega - T_\omega \tag{1.1}$$

Where, A_ω is the absorption coefficient, R_ω is the reflection loss and T_ω is the transmission loss. Apparently, absorption is maximum when both reflection loss and transmission loss are simultaneously minimum. The subscript, ω, shows dependence of the absorption on frequency of the incident wave. In conductor backed absorbers $T_\omega = 0,$ making equation (1.1)

$$A_\omega = 1 - R_\omega \tag{1.2}$$

The basic absorption mechanism schematic for a conductor backed single layer conventional absorber is depicted in Figure 1.2(a).

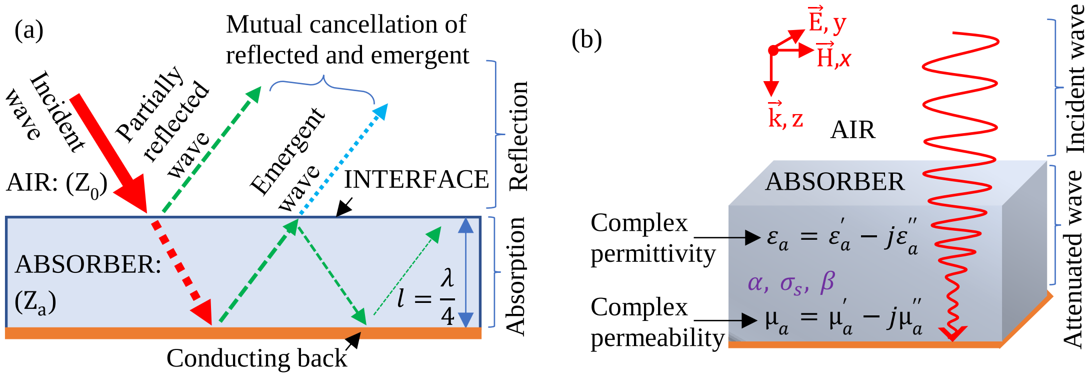

Figure 1.2 Schematic of a (a) conducting back single layer absorber's working and (b) propagation of electromagnetic wave through an absorber.

If z-axis is taken as the direction of incidence of uniform plane wave with E-field along y-axis and H-field along x-axis, as schematized in Figure 1.2(b), the following expressions for E-field and H-field inside the absorber [43-49] are,

$$\vec{E} = \vec{E}_y \hat{a}_y = E_0 e^{-\gamma z} \hat{a}_y \tag{1.3}$$

$$\vec{H} = -\frac{1}{j\omega\mu_a} \vec{\nabla} \times \vec{E} = \frac{\gamma}{j\omega\mu_a} E_0 e^{-\gamma z} \hat{a}_x = \vec{H}_x . \hat{a}_x \tag{1.4}$$

Where, $\vec{E}$ and $\vec{H}$ is the electric and magnetic vector respectively, $\gamma = \sqrt{j\omega\mu_a(\sigma_s + j\omega\varepsilon_a)} = \alpha + j\beta$ is the propagation constant. α here being the attenuation constant and β the phase constant. ω is the angular frequency, $\mu_a = \mu_0\mu_r$ is the permeability, σ_s is the conductivity here and $\varepsilon_a = \varepsilon_0\varepsilon_r$ is the permittivity. $\mu_a = \mu_a' - j\mu_a''$ and $\varepsilon_a = \varepsilon_a' - j\varepsilon_a''$ are the complex forms of permeability and permittivity of the absorber. The imaginary parts in both the complex quantities relates to the losses of the absorber [43, 50, 51].

The ratio of the electric to magnetic field magnitudes at the air absorber interface is known as the intrinsic or characteristic impedance and is denoted as η,

$$\eta = \frac{\vec{E}_y}{\vec{H}_x} = \frac{E_0 e^{-\gamma z}}{\frac{\gamma}{j\omega\mu} E_0 e^{-\gamma z}} = \frac{j\omega\mu}{\gamma} = \frac{j\omega\mu_0\mu_a}{j\omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_a\mu_a}} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\sqrt{\frac{\mu_a}{\varepsilon_a}} = Z_0\sqrt{\frac{\mu_a}{\varepsilon_a}} \tag{1.5}$$

Where, $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ and $\sqrt{\frac{\mu_a}{\varepsilon_a}} = Z_a$ represents the free space and absorber's characteristic impedance respectively.

At the air-absorber interface, the impedance mismatch determines the extent of reflection of the incident EM wave. For matching interface, the real part of $Z_a = Z_0 = 377\Omega$, and the imaginary part of Z_a should be approaching zero. This condition is achievable only when $\sqrt{\frac{\mu_a}{\varepsilon_a}} \cong 1$. Ratio of reflected to incident EM energy, termed as reflection loss (RL) and for a conducting back microwave absorber, mathematically, it is expressed as [50]

$$RL = \frac{Z_a - Z_0}{Z_a + Z_0} \tag{1.6}$$

In meta-structure absorbers (MSA) Figure 1.3(a) however, impedance matching is achieved by manipulating the dimensions of sub-wavelength structures developed using high lossy materials, periodically arranged in low loss matrix to realize metamaterial like tailored effective complex permittivity and permeability [42, 43, 48, 52-57]. Once the impedance is matched, the incident EM wave penetrates the absorber and suffers an exponential decay by a factor $e^{-\alpha z}$. Here, z is the distance travelled by the EM wave in the MSA and α is the attenuation constant expressed for dielectric absorber ($\sigma_s = 0$),

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{(\mu_a''\varepsilon_a'' - \mu_a'\varepsilon_a') + \sqrt{(\mu_a''\varepsilon_a'' - \mu_a'\varepsilon_a')^2 + (\varepsilon_a'\mu_a'' + \varepsilon_a''\mu_a')^2}} \qquad (1.7)$$

Where, f is the frequency of the penetrating EM wave and $c = 1/\sqrt{\varepsilon_0\mu_0}$ is the speed of EM wave in free space.

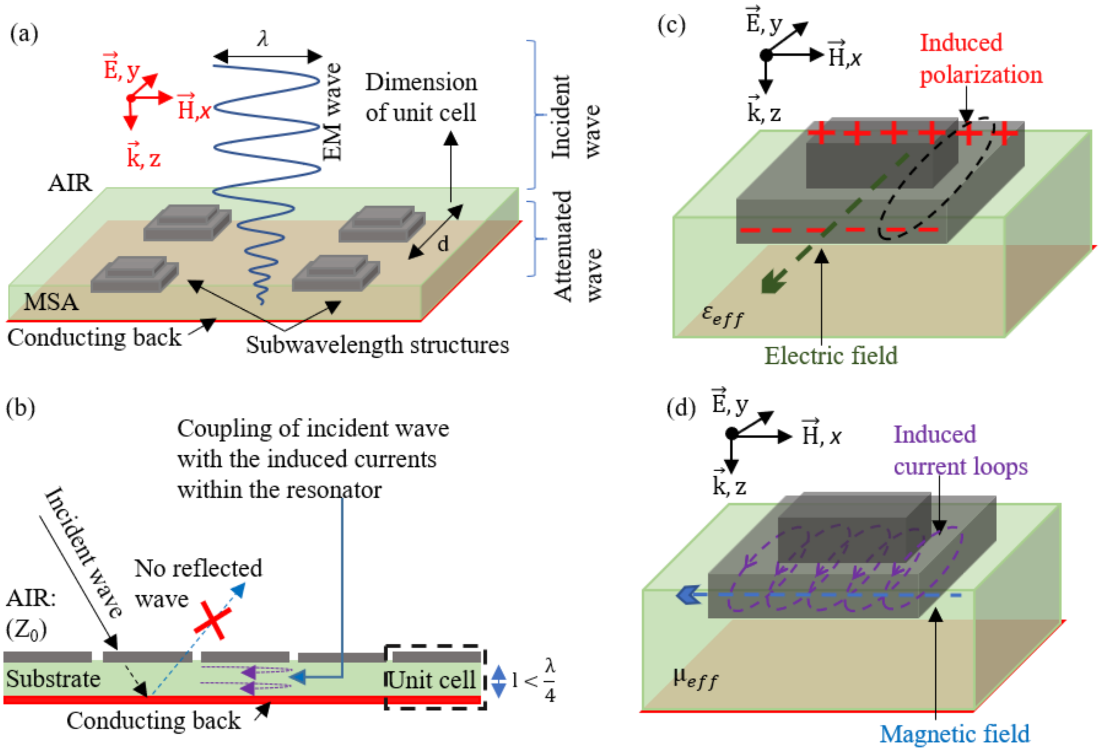

Figure 1.3 Schematic of (a) propagation of EM wave in a meta-structure absorber, (b) and (c) working of a meta-structure absorber.

In conventional absorbers, reflections are reduced through phase cancellation by matching absorber's thickness to quarter wavelength ($\lambda/4$) of the intended frequency, Figure 1.2(a). In MSA, the oscillating electric field component leads to two different mechanism - 1) charges get accumulated at the edges of the resonators due to difference in permittivity values of the resonator and the matrix resulting in formation of electric dipoles which gives rise to effective permittivity Figure 1.3(c); 2) the oscillating dipoles induces current loops and hence magnetic ‘dipoles’, which couples with the penetrated magnetic component of the EM wave, Figure 1.3(d), giving rise to effective permeability. The two combined, assists in achieving the impedance matching condition given by equation- $Z_a = Z_0$ [52, 53, 58, 59]. The mechanism also make resonance independent of the absorber’s thickness in MSAs [60-62]. The penetrated wave attenuates partially by local resonance in the structures and partially by high loss of the dielectric resonator material in a meta-structure absorber resulting in a wide absorption bandwidth.

1.4 THESIS OUTLINE

The proposed work, ranges from - selection, preparation and characterization of materials for both the resonators and matrix to development and testing of performance of the fabricated absorber.

In line with the objectives, the thesis has been framed into 7 chapters. A brief introduction to meta-structure absorbers is provided in the first chapter culminating with its current state of research. The literature review sheds light on the inherent challenges and gaps in the subject's current research.

Hydrogel is selected as a potential substitute for water to develop flexible embedded resonators in ***chapter II***. Here, flexible silicone rubber is utilized as matrix. The structures are designed and optimized for maximum absorption followed by development of the meta-structure absorber and measurement of absorption performance.

In ***chapter III***, dual resonating structures with 4-fold and 6-fold symmetry are used to enhance bandwidth of hydrogel based MSAs to cover the whole operating band. Performance restoration tests are conducted with the developed absorbers.

Chapter IV demonstrates deep eutectic solvent (DES) gel as replacement to hydrogel resonators in MSA which offers higher attenuation. The fabricated absorber is evaluated for its radar cross section (RCS) and its effectiveness in lowering RCS.

The DES gel resonator's geometry is modified in ***chapter V*** to obtain a more stable structure for good retraction after bending/stretching. Antenna isolation studies are conducted using the designed absorber.

An effort is made to develop optically transparent DES gel MSA by substituting opaque silicone matrix with transparent urethane rubber. The metal reflecting back is replaced by optically transparent alternatives like metal mesh. The absorber is investigated for potential use in solar panel camouflage. All these studies are placed in ***chapter VI***.

The efficacy of the proposed meta-structure absorbers in plethora of X-band applications, is summed up in ***chapter VII***.

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