2: Literature Review and Motivation

In this chapter, microwave absorbers are reviewed and classified according to the design approach, materials, physical mechanism and fabrication techniques. Bandwidth enhancement using engineered planar structures and their fabrication feasibility are discussed. It is found that introducing additional resonance modes improves bandwidth. This chapter elaborates the motivation of the thesis: to design and fabricate bandwidth-enhanced absorbers using engineered planar structures.

2.1 CLASSIFICATION OF MICROWAVE ABSORBERS

Microwave absorbers are categorized according to design approach viz. classical microwave absorbers, material based absorbers and metamaterial absorbers. In this section, different classes of absorbers are reviewed for design methodology and practical limitations.

2.1.1 Classical Microwave Absorbers

(a) Salisbury Screen Microwave Absorber (SSMA)

Salisbury Screen Microwave Absorber (SSMA) was invented by an American engineer Winfield Salisbury in 1952 [Salisbury, 1952]. The SSMA was used to reduce the backscatter from the metallic surface. The SSMA is a passive microwave device which consists of a resistive sheet separated by quarter-wavelength thick dielectric metal back substrate, as shown in Figure 2-1(a) [Chambers, 1994]. Minimum reflection is observed due to impedance matching condition, as shown in Figure 2-1(b).

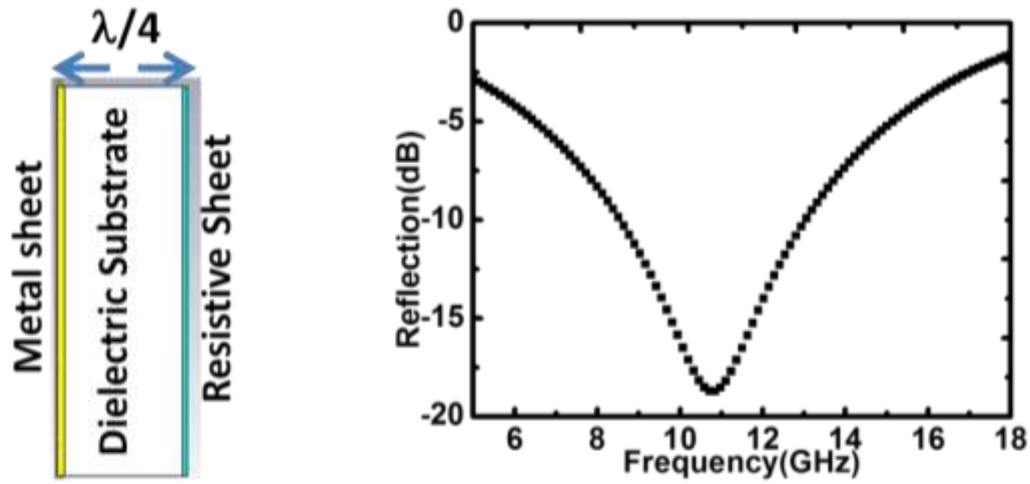
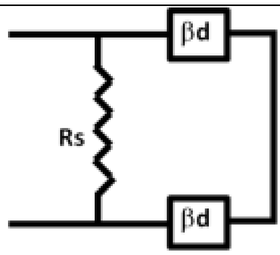


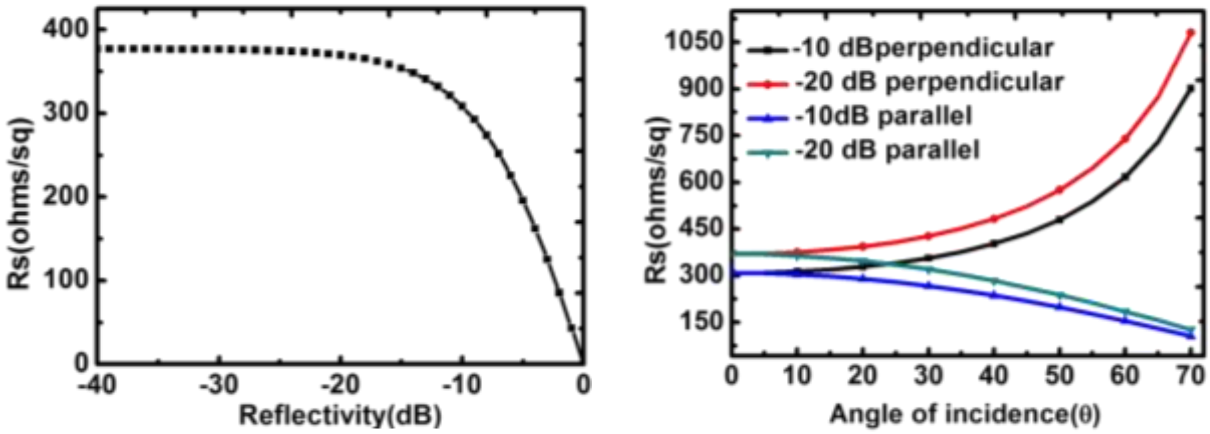
Figure 2- 1: (a) Schematic of SSMA (Source: Chambers, 1994) (b) Typical performance of SSMA for Rs=308Ω/sq, d=3.2mm and ε=4.2

Table 2- 1 presents the equivalent circuit model and equations about design the SSMA [Chambers, 1994], [Fante and Mccormack, 1988]. The resonant frequency of the SSMA can be tuned by sheet resistivity, thickness and substrate permittivity. The central frequency depends on the dielectric substrate thickness and permittivity.

Table 2- 1: Parameters associated with SSMA [Chambers, 1994]

Equivalent Circuit	
Reflection coefficient (ρ)	$\rho = \frac{Y_0 - Y_{in}}{Y_0 + Y_{in}}$
Input impedance	$Y_{in} = G - jYcot\beta d$ $G = \frac{1}{R_s}, Y = Y_0\sqrt{\varepsilon}\ and\ \beta = \frac{2\pi f\sqrt{\varepsilon}}{c}$
Central frequency	$f_c = \frac{c}{4\sqrt{\varepsilon}d}$
Optimum resistivity	$G_{opt} = Y_0\left(\frac{1+\rho\rho^*}{1-\rho\rho^*}\right)$
Optimum resistivity for perpendicular polarization	$G_{opt\theta} = Y_0 cos\theta\left(\frac{1+\rho\rho^*}{1-\rho\rho^*}\right)$
Optimum resistivity for parallel polarization	$G_{opt\theta} = \frac{Y_0}{cos\theta}\left(\frac{1+\rho\rho^*}{1-\rho\rho^*}\right)$
Normalized Bandwidth (BW)	$NBW = \frac{2(f_c - f)}{f_c}$

The optimum sheet resistivity varies with reflection level, as shown in Figure2-2(a). For example, the optimum sheet resistivity is 308 Ω/sq for -10 dB reflection. The optimum sheet resistivity varies with the angle of incidence for parallel and perpendicular polarizationsFigure 2-2(b) and Table 2- 1). The performance of the SSMA varies with the incident angle for parallel and perpendicular polarization.



(a) (b)

Figure 2- 2: (a) Variation of sheet resistivity with reflection level (b) variation of sheet resistivity for maximum bandwidth with the angle of incidence and polarization (Source: Chambers, 1994)

The dielectric substrate with higher/lower permittivity results in lower/higher normalized bandwidth (NBW), as shown in Figure 2-3. For example, spacer with ε=1, NBW= 75.1% whereas for FR4 (ε=4.2) NBW= 40.12%.

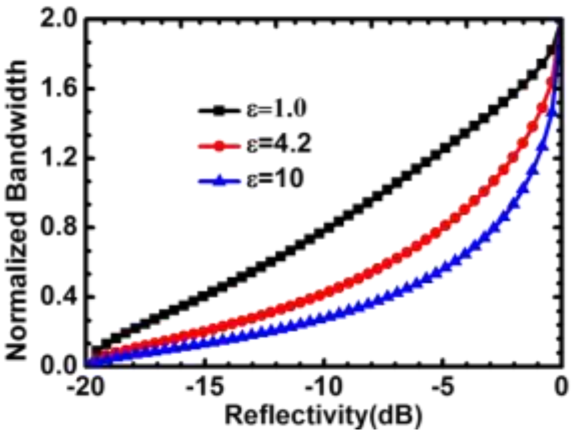
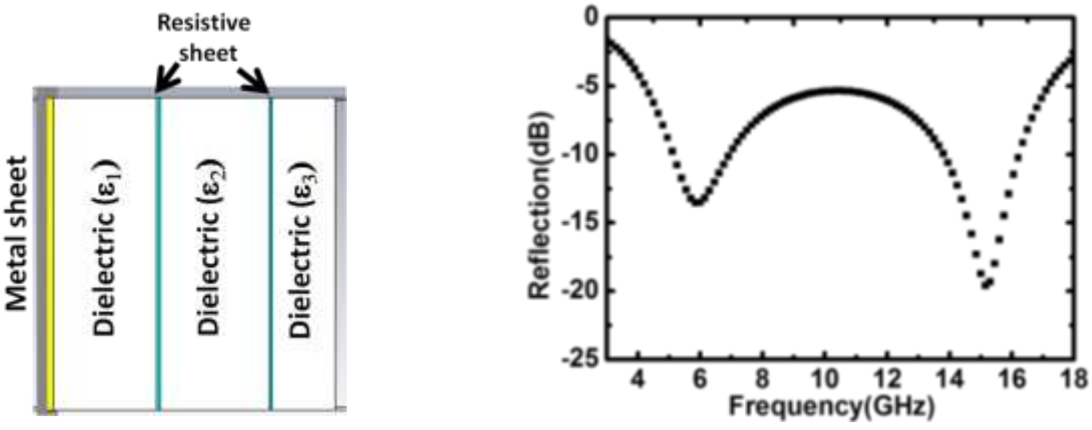


Figure 2- 3 : Normalized bandwidth vs reflectivity level for specified spacer permittivity (Source: Chambers, 1994)

2.1.1 (b) Jaumann Absorber : Multi-layer Salisbury Screen

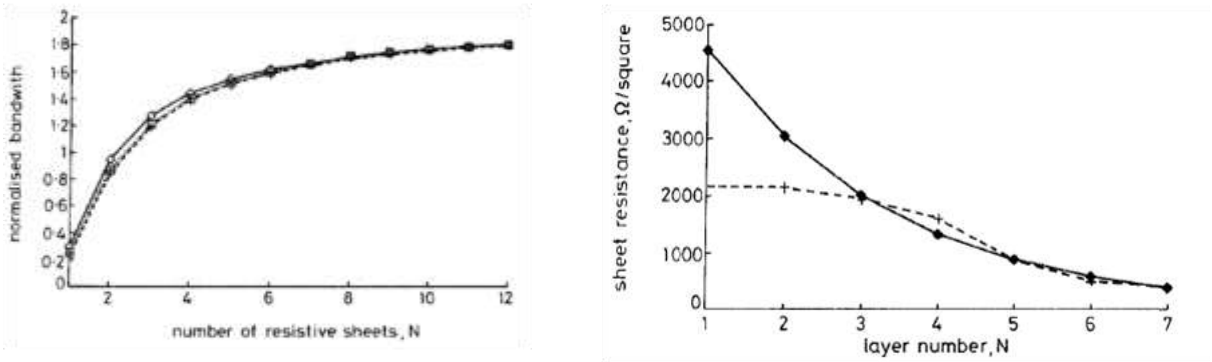
Jaumann Absorber (JA) is a stack of resistive sheets separated by quarter-wavelength thick dielectric substrate from the metal ground plate as shown in Figure 2-4(a) [Chambers and Tennant, 1994], [Chambers and Tennant, 1996]. SSMA is single layer JA. JA shows multiple resonant modes as it consists of multiple SSMAs, as presented in Figure 2-4(b). The wideband JA can be realized by overlapping of resonant modes for the tuned design parameters viz. resistive sheets, substrate permittivity and thickness. The optimization of design parameters and performance of JA can be simulated using transmission line approach [Pozar, 2005].



(a) (b)

Figure 2- 4: (a) Schematic of Jaumann absorber (b) Typical response of Jaumann absorber (Source: Chambers and Tennant, 1996)

A large number of layers along with customized sheet resistivity is required for designing wideband absorber, as shown in Figure 2-5.



(a) (b)

Figure 2- 5: (a) Normalized bandwidth vs the number of layers for spacer permittivity ε=1.1 (b) resistive sheet profile for N=7 and ε=1.1 (Source: Chambers and Tennant, 1996)

2.1.2 Material Based Absorbers (MBA)

It is evident from Maxwell equations that the time-varying electric and magnetic fields are coupled to each other and behave like as waves. EM wave propagation in the medium is governed by complex propagation constant (γ), as Table 2- 2. The real part of propagation constant defines the attenuation of EM wave by the medium, whereas the imaginary part indicates the phase constant. The attenuation of EM wave characterized by attenuation constant and distance traversed ($e^{-\alpha z}$). The attenuation constant depends on the material medium parameters viz. real and imaginary parts of permittivity and permeability.

The impedance of the metal back material based absorbers can be tailored to free space impedance by material parameters (ε and μ) and thickness of the absorber as Table 2- 2 which results in low reflection due to impedance matching condition. The material parameters (ε and μ) can be tuned and realized by adding conducting/magnetic fillers in an epoxy matrix [Qin and Brosseau, 2012].

The material based absorbers are further categorized as dielectric or magnetic absorbers based on their ability to suppress the incident electric or magnetic fields, respectively [Qin and Brosseau, 2012]. The carbon fibre, conducting carbon, carbon black and graphene are considered as electric fillers whereas iron and nickel are considered as magnetic fillers.

Table 2- 2: EM wave parameters in a material medium

Propagation constant (γ) [Saville, 2005]	$\gamma = \alpha + j\beta$ $\alpha = \frac{\omega}{\sqrt{2}c}\sqrt{\varepsilon''\mu'' - \mu'\varepsilon' + \sqrt{(\mu'^2 + \mu''^2)(\varepsilon'^2 + \varepsilon''^2)}}$ α=attenuation constant, β=phase constant
Wave Impedance for metal back material [Qin and Brosseau, 2012]	$Z_d = Z_0\sqrt{\frac{\mu}{\varepsilon}}\tanh\left(j\frac{2\pi f d\sqrt{\varepsilon\mu}}{c}\right)$ Z0=free space impedance, d=thickness, f=frequency
Bandwidth of dielectric absorber [Rozanov, 2000]	$\lambda \approx \frac{32}{\pi}\rho Re(\mu)d$, ρ=reflection coefficient
Minimum Thickness for dielectric absorber [Rozanov, 2000]	$d_{min} \approx \frac{\lambda_{max}}{17.2}$

The designing of material based absorbers are considered a perpetual problem due to the limited tuning of material parameters. The approximated bandwidth of the material based absorbers largely depends on thickness, reflection coefficient and real part of the permeability as given in Table 2- 2. The increase in thickness and real part of permeability of the absorbers result in large bandwidth. In contrary, the design of low reflection absorbers requires large thickness. The bandwidth is independent of the permittivity of the absorbers.

For a magnetic absorber, the permeability of the material cannot be tuned to the desired level because of Snoek's law [Snoek, 1948]. For designing reflectionless dielectric absorbers, the following condition should satisfy; $Re(\varepsilon) \propto \frac{1}{f^2}\, and\ Im(\varepsilon) \propto \frac{1}{f}$ [Rozanov, 2000]. The bandwidth of the absorbers is independent of the permittivity Table 2- 2. The design of dielectric absorbers demands minimum thickness requirement, which depends on the operating wavelength. The thickness requirement of dielectric absorbers is large for low-frequency regions. For example, the minimum thickness for X-band dielectric absorber for -10 dB reflection is 2.1mm approximately.

Moreover, the arbitrary values of material parameters cannot be considered due to their dependence by Kramers-Kronig relation [Rozanov, 2000]. The experimental or reported values should be considered for designing material based absorbers.

The dielectric absorbers offer less weight penalty and large thickness because of the low density of conducting fillers. In contrast, magnetic absorbers offer large weight penalty and low thickness due to the high density of the magnetic fillers. Further, the thickness requirement for magnetic absorbers is less in comparison to dielectric absorbers. A trade-off is required based on application and necessity for designing material based absorbers.

2.1.3 Metamaterial Absorbers

The first application of the metamaterial as absorber was demonstrated by Landy, as shown in Figure 2-6[Landy *et al.*, 2008]. The unit cell consists of electric ring resonator (ERR) on the front side and cut wire on the backside. The ERR and cut wire are made up of copper metal printed on FR4 substrate.

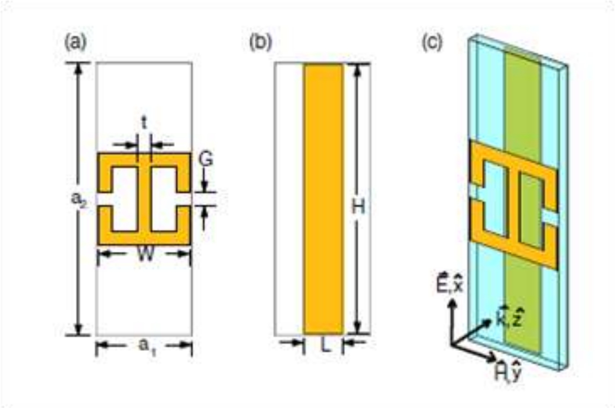
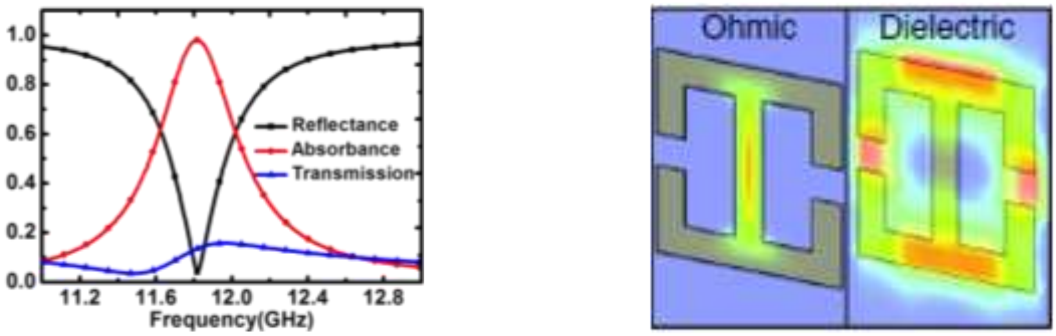


Figure 2- 6: Unit cell of absorber consists of (a) Electric ring resonator (ERR) on the front side (b) cut wire on the backside (c) unit cell of the designed absorber (Source: Landy et al., 2008)

The reported absorber was fabricated using optical lithography technique. The performance of the absorber was measured using Vector Network Analyzer and a pair of Horn antenna. The operational frequency of the absorber is 11.7 GHz, as shown in Figure 2-7(a). The absorbance of microwave absorber can be calculated using equation $A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$ without metal back and $A(\omega) = 1 - |S_{11}|^2$ with metal back. The S_{11} and S_{21} represents the reflection and transmission in terms of scattering (S) parameters. The reported absorber almost absorbs the incident wave at 11.7 GHz due to low reflection and transmission. The losses simulated at absorbing frequency, arise due to the lossy components viz. conductivity of copper and loss tangent of FR4 substrate (Figure 2-7(b)). The ohmic losses are confined in the metallic part. The confinement of electric field yields in dielectric losses. The dielectric losses are dominating in comparison to ohmic losses.

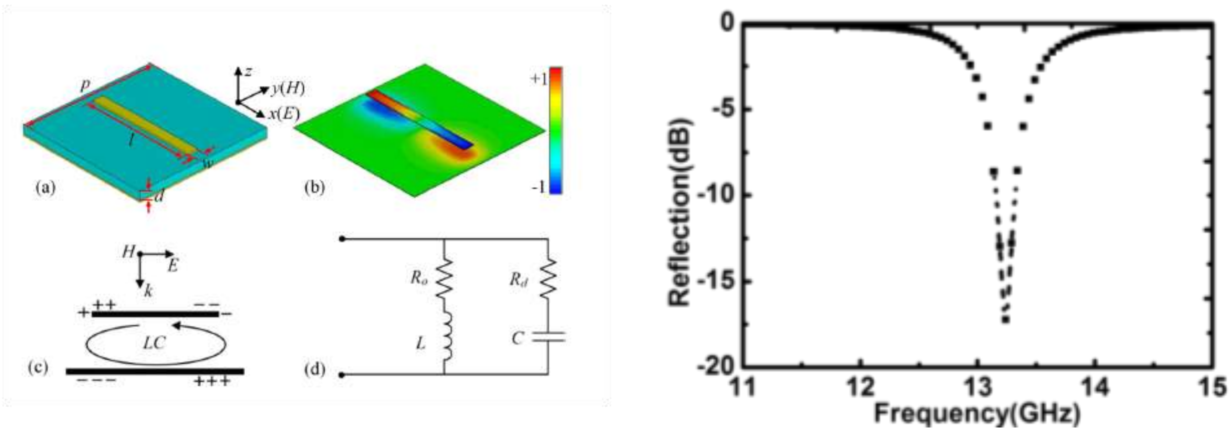


(a) (b)

Figure 2- 7: Simulated transmission, absorption and reflectance of the absorber formed by infinite periodic arrangement of the unit cell shown in Figure 2-6 (b) Loss mechanism in the absorber using field quantities (Source: Landy et al., 2008)

The physical insight of metamaterial absorbers is described by the RLC circuit. The resistance (R) induces owing to the finite conductivity of metal and dielectric loss tangent of the substrate. The inductance (L) arises because of circulating currents loops confined in between upper metallic geometry and lower metallic plate. Coupling between the unit cell geometry and sandwiched dielectric substrate between the upper metallic geometry and lower metallic plate induce capacitance (C) [Dayal and Ramakrishna, 2012]. For example, the equivalent circuit model of wire-based metamaterial absorber comprises of the L, C, R_o, R_d as presented in Figure 2-8 (a) [Pang *et al.*, 2013]. The reported absorber comprises of copper wire element printed on metal back FR4 substrate. The circulating currents loops in wire element and back metal plate induces L. The sandwiched FR4 substrate in between wire element, and back metal plate introduces C. The finite conductivity of copper and loss tangent of FR4 substrate contribute as R_o and R_d respectively.

The resonant frequency of the RLC circuit expressed as $\omega = \frac{1}{\sqrt{LC}}$. For example, the resonant frequency for wire absorber in terms of absorber parameter is expressed as $f \approx \frac{1}{l\sqrt{\varepsilon}}$. The resonant frequency of wire absorber can be tuned by wire length and substrate permittivity. The metamaterial absorbers offer flexibility in terms of tuning the resonant frequency by changing the unit cell dimensions and substrate parameters. The quality factor of the RLC circuit is expressed as $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$ [Gu *et al*, 2010]. The metamaterial absorbers based on metallic geometry suffer from the narrow bandwidth characteristics. The wide bandwidth absorber can be designed using resistive components viz. resistive sheet/inks.



(a)

(b)

Figure 2- 8: (a) Unit cell of wire-based absorber along with equivalent circuit model (b) simulated response of the absorber [Source: Pang et al., 2013]

The microwave metamaterial absorbers consist of metallic geometries printed on metal back FR4 substrate. The metallic geometries are of copper metal with electric conductivity of 5.8×10^7S/m. The permittivity and loss tangent of FR4 is 4.2 and 0.02, respectively. The wide bandwidth absorbers are designed, fabricated and measured at microwave frequency regions [Bhattacharyya, 2016], [Bhattacharyya *et al.*, 2015] [Sood and Tripathi, 2015] as shown in Figure 2-9. The unit cell, thickness and bandwidth of the absorber shown in Figure 2-9 (a) and (b) are 8mm, 3.2mm and 8.3GHz (6.86 to15.16 GHz) for -10dB refection respectively [Bhattacharyya *et al.*, 2015]. Similarly, the unit cell, thickness and bandwidth of the absorber shown in Figure 2-9(c) and (d) are 4.5mm, 1.54mm and 3.75 GHz (8.6 to12.35 GHz) for -10dB refection respectively [Sood and Tripathi, 2015].

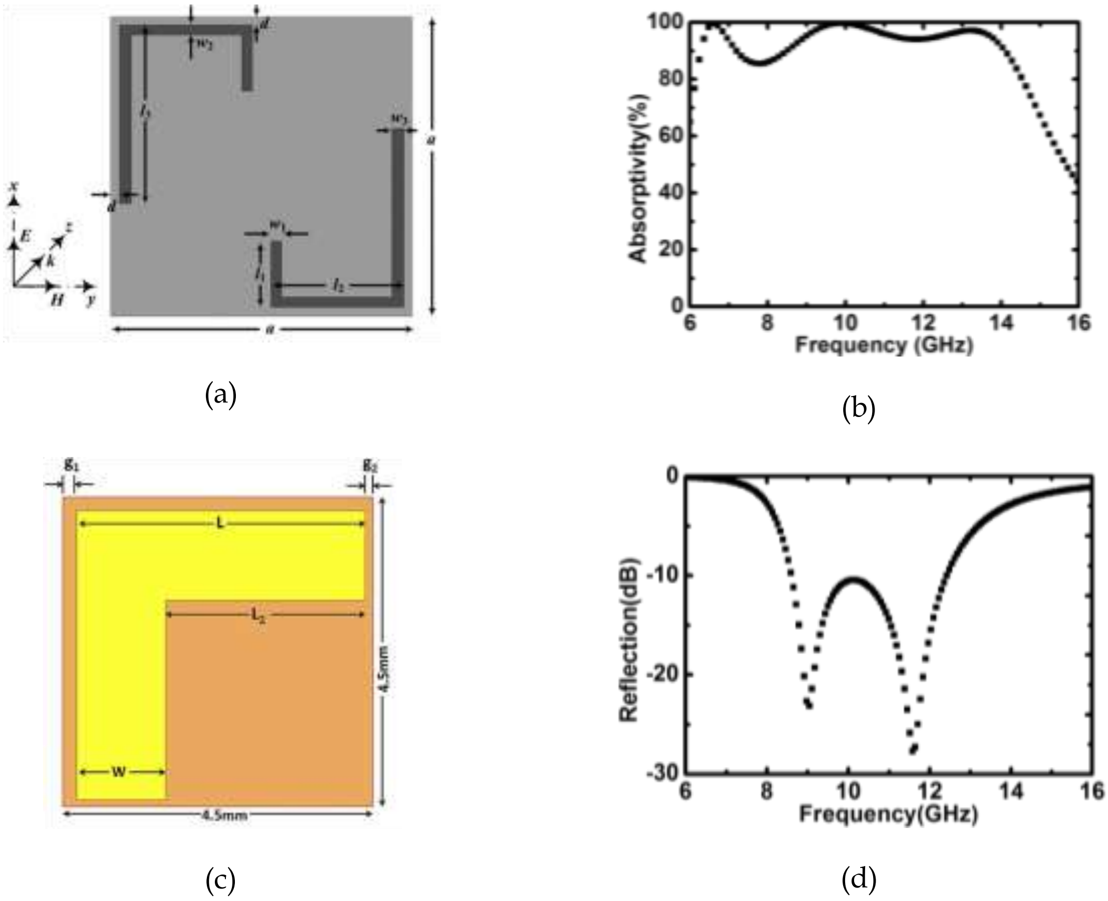
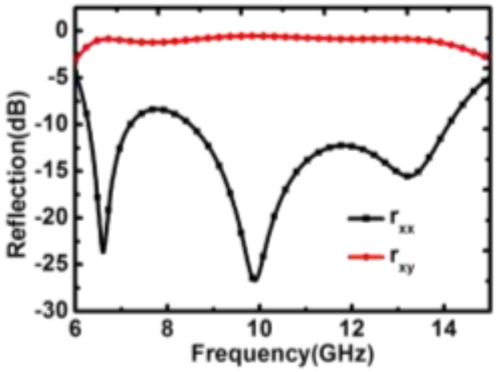
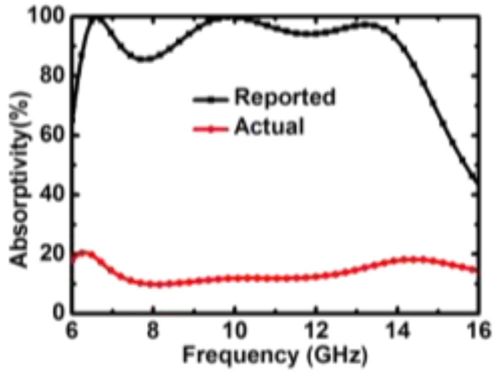


Figure 2- 9: (a) and (b) Unit cell design and simulated response of wideband absorber using copper metal and FR4 substrate (Source: Bhattacharyya, et al., 2015) (c) and (d) Design and simulated response of wideband absorber using copper metal and FR4 substrate (Source: Sood and Tripathi, 2015)

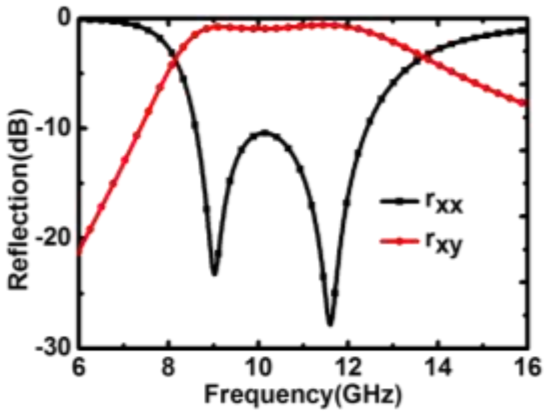
These absorbers are simulated, analyzed and measured in co-polarization configuration. The response of these wide bandwidth absorbers is analyzed in cross-polarization as shown in Figure 2-10 (a) and (c) [Kundu *et al.,* 2017], [Tian *et al.,* 2016]. The reported absorbers are showing high reflection in cross-polarization. The high cross-polarization and low co-polarization reflections of absorbers are attributed to the absence of resistive components. The effective absorbance of these absorbers is less than 20%, as shown in Figure 2-10 (b) and (d). They are termed as polarization converter because of high cross-polarization and low co-polarization reflection. It is imperative to analyze the designed absorbers consisting of FR4 and metallic geometries in co and cross-polarization.



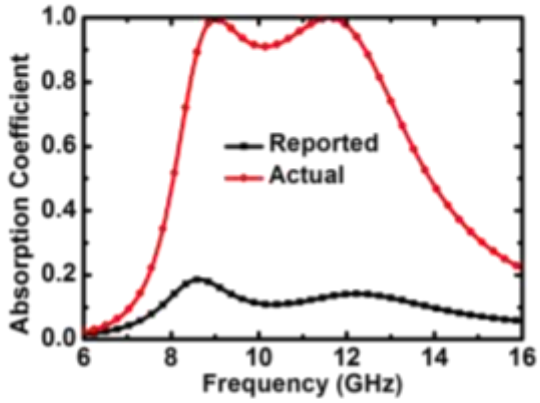
(a)



(b)



(c)



(d)

Figure 2- 10 :(a) and (b) Simulated response of the absorber in co and cross-polarization and effective absorbance (Source: Kundu et al., 2017) (c) and (d) Simulated response of the absorber in co and cross-polarization and effective absorbance (Source: Tian et al., 2016)

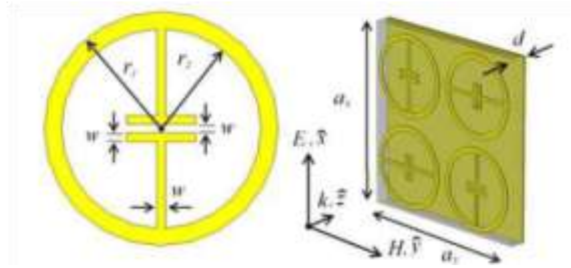
2.2 BANDWIDTH ENHANCEMENT TECHNIQUES

The microwave absorbers consisting of engineered planar structures are showing narrow bandwidth characteristics due to the absence of resistive/lossy component. The reported techniques indicate that introduction of additional resonance modes helps in bandwidth enhancement viz. combination of multiple geometries in the unit cell, scaling of the unit cell, overlapping of resonance modes by optimizing of design parameters and applications of resistive ink.

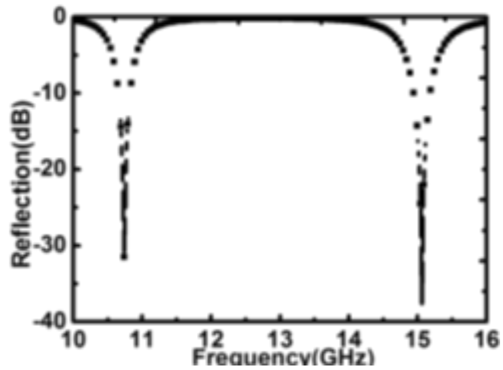
2.2.1 Multiple geometries in the unit cell

The multiple resonances can be introduced by designing a unit cell with multiple geometries. The reported dual-band polarization-insensitive absorber is presented in Figure 2-11(a) [Li *et al.*, 2010]. We simulated this structure in CST, and the results are shown in Figure 2-11(b). The reported resonance modes are observed at 11.15 GHz and 16.01 GHz. Note the slight variation in the simulated and the reported results, which can be attributed to the variation of material parameters of the substrate used in the simulation and the experiment. The unit cell size and thickness of the absorber are 12mm and 0.5 mm, respectively. The simulated field quantities at absorbing frequencies reveal that the resonance mode at 11.15 GHz is due to ring element, whereas the 16.01 GHz is attributed to inner plates Figure 2-11(c) and (d). The multi-

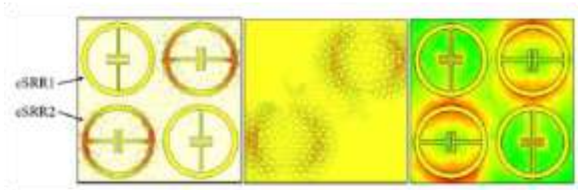
`
band absorbers using this technique with different configuration are designed and characterized [Chaurasiya et al., 2015], [Li *et al.*, 2010], [Shen *et al.*, 2011].



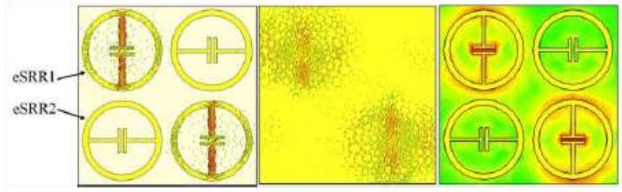
(a)



(b)



(c)



(d)

Figure 2- 11: (a) Unit cell of designed dual-band absorber (b) simulated response (c) and (d) simulated field quantities at 11.15 GHz and 16.01 GHz respectively (Source: Li et al., 2010)

2.2.2 Scalability of unit cell geometry

The multiple resonance modes can be introduced by scaling of the unit cell geometry. The unit cell of these absorbers consists of a periodic arrangement of basic and scaled geometry. The scaling up of the basic geometry shifts the resonance mode to a lower frequency and vice versa. For example, the dual/triple band absorber using this approach is shown in Figure 2-12 [Li *et al.*, 2011]. The single band electric-field-coupled (ELC) resonator with the simulated response is shown in Figure 2-12(a) and (d). The dual-band absorber consists of a periodic arrangement of ELC resonator and its scaled version, as shown in Figure 2-12(b). Figure 2-12(e) shows that the resonance frequency shifts to lower frequency with increasing of the scaling factor. The triple band absorber can be realized by designing a unit cell with three scaling geometries, as shown in Figure 2-12(c) and (f). The multiband absorbers with different configuration using a scaling of the unit cell are designed, physically realized and characterized [Bhattacharyya *et al.*, 2013].

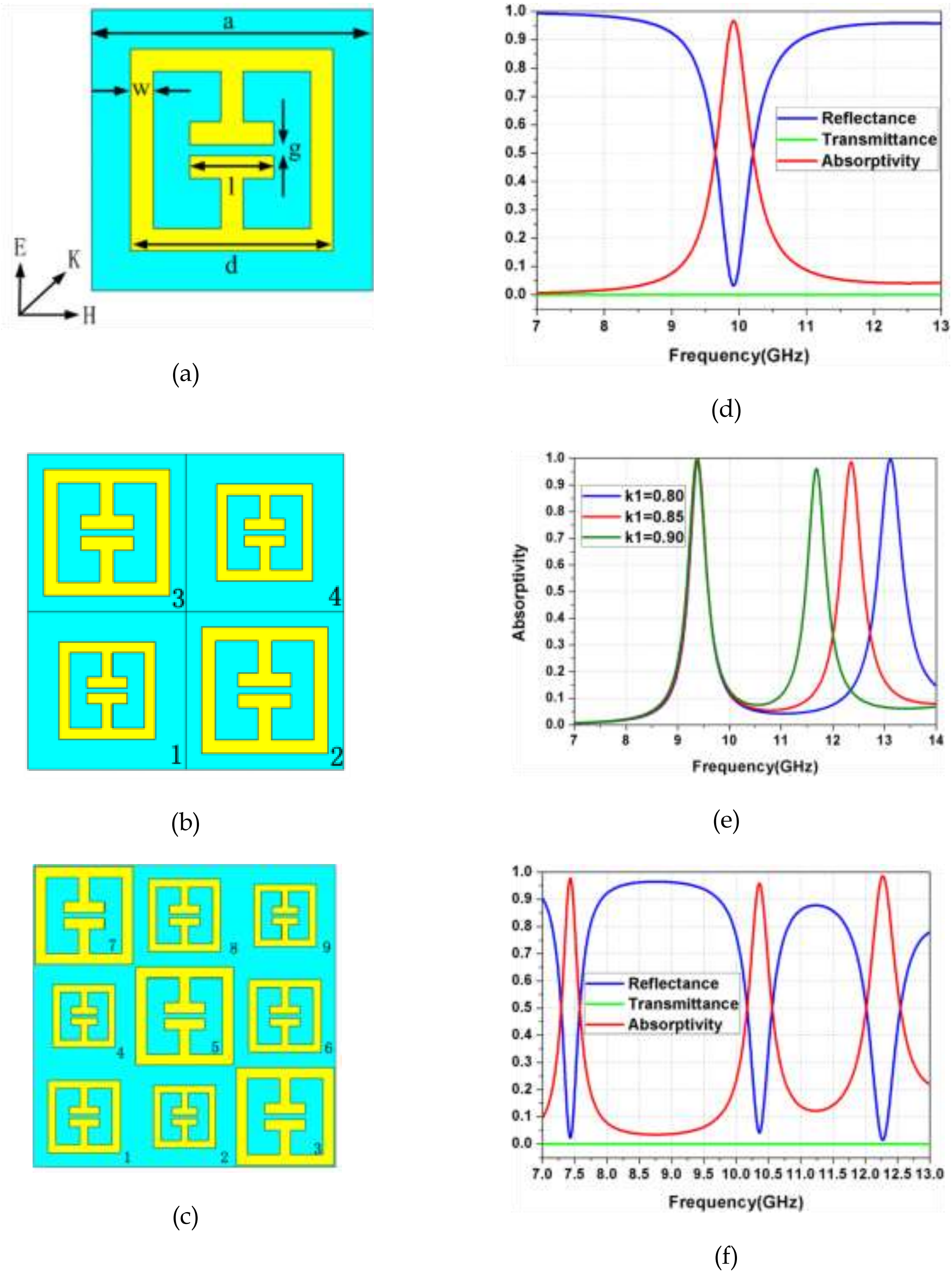
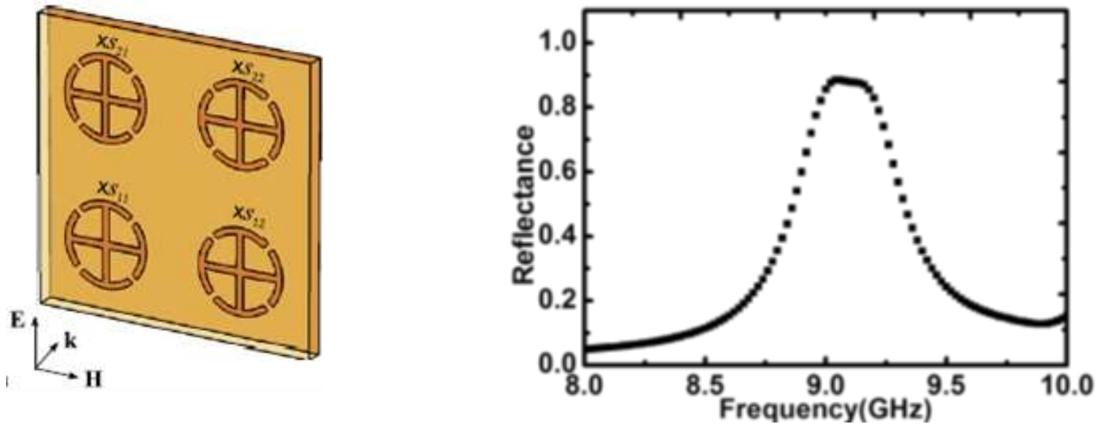


Figure 2- 12 :(a), (b) and (c) Unit cell design of single, dual and triple-band absorber by scaling of the unit cell respectively (d), (e) and (f) simulated response (Source: Li et al., 2011)

2.2.3 Overlapping of resonance modes

Multiband absorbers can be designed with the unit cell consisting of different geometries. The introduction of additional resonance mode results in bandwidth enhancement. Designing and optimizing design parameters viz. scalability of the unit cell, the bandwidth of the absorbers can be further improved. For example, an enhanced absorber based on circumscribed-cross resonator along with simulated reflection is shown in Figure 2-13[Dimitriadis *et al.*, 2012]. The optimization of scaling factors leads to the overlapping of resonance modes which results in bandwidth enhancement in terms of the Full Width at Half

`
Maximum (FWHM). The other reported absorbers with different configuration are designed, fabricated, physically realized and characterized [Bhattacharyya *et al.*, 2013], [Ghosh *et al.*, 2014] [Lee and Lim, 2011].



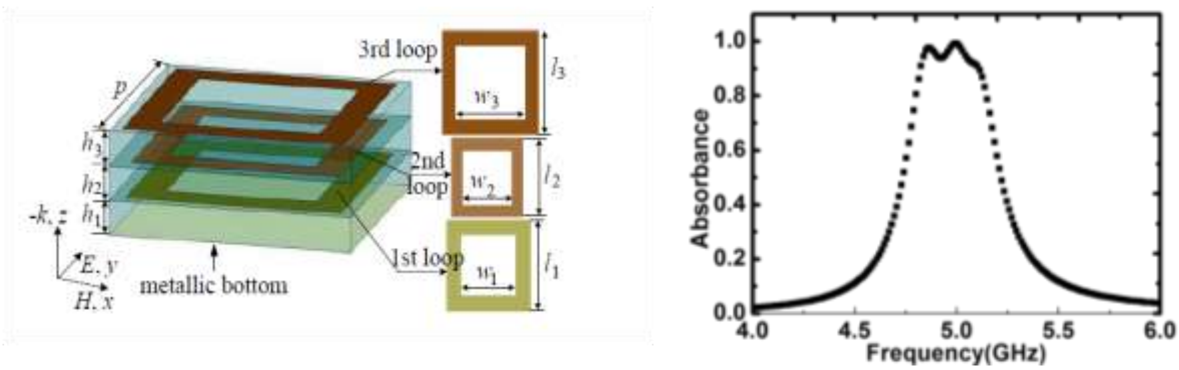
(a)

(b)

Figure 2- 13: (a) and (b) Unit cell design and the simulated response of the absorber respectively (Source: Dimitriadis et al., 2012)

2.2.4 Multi-layer approach: Scaling of the unit cell

Scaling of the unit cell can be done alternatively by a multilayer approach. For example, the bandwidth-enhanced absorber consisting of square loops in the three-layer configuration is shown in Figure 2-14 along with simulated response [Yang *et al.*, 2013]. Optimization of design parameters viz. thickness of the substrate and square loop dimensions, the introduced resonance modes overlapped and results in bandwidth enhancement. The other reported absorbers based on this configuration are reported in [Xiong *et al.*, 2013] and [Sun *et al.*, 2011]].



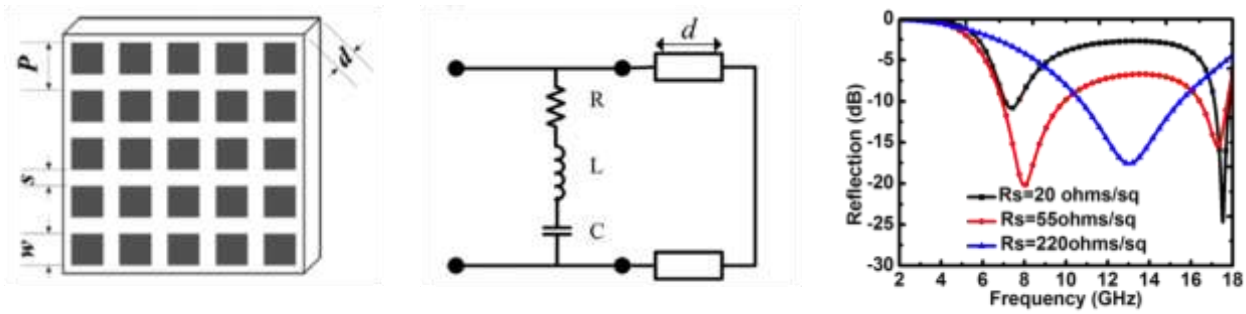
(a)

(b)

Figure 2- 14 : (a) and (b) Unit cell design and the simulated response of the absorber (Source: Yang et al., 2013)

2.2.5 Resistive inks/sheet

Due to the absence of lossy/resistive components, the bandwidth of the absorbers is narrow. The bandwidth of the absorbers can be enhanced significantly using resistive component due to lowering of quality factor [Gu *et al.*, 2010]. For example, resistive square patch-based absorber along with simulated response for different sheet resistivity and sheet thickness with 0.1mm is shown Figure 2-15(a) and (c) [Pang *et al.*, 2011]. The additional resonance mode is induced due to the formation of lossy RLC resonance circuit because of square patches geometry, as shown in Figure 2-15 (b). In the absence of the resistive square patches, the designed absorber function as Salisbury Screen Microwave Absorber. Using resistive sheets, different absorbers are reported with improved bandwidth are designed and characterized [Sun *et al.*, 2012].



(a) (b) (c)

Figure 2- 15: (a), (b) and (c) Unit cell design, equivalent circuit and the simulated response of the resistive ink-based absorber respectively (Source: Pang et al., 2011)

2.3 SUMMARY OF THE REPORTED ABSORBERS

Table 2-3 summarizes the comparison of existing microwave absorbers along with fabrication and advantages.

Table 2-3: Summary of different classes of microwave absorbers along with fabrication and advantages

Class of absorbers	Fabrication	Advantages
Classical absorbers	Salisbury screen absorber: resistive sheet placed quarter wavelength distance from the ground plate	Used for minimizing reflectivity from metal
	Jaumann Absorber: Combination of the SSMA, multilayer absorber	Wideband absorber due to multilayer configuration
Material Based absorbers	Realized as composites (dielectric and magnetic) of conducting fillers in the epoxy matrix	By tailoring thickness and material parameters the resonance frequency can be tuned Available in paint and rubber sheets for application on curved surfaces
Metamaterial Absorbers	Realized as engineered planar metallic structures printed on the metal back dielectric substrate	Ease of fabrication using low-cost screen printing technique, nearly perfect absorption, low thickness and tuning of the resonance frequency

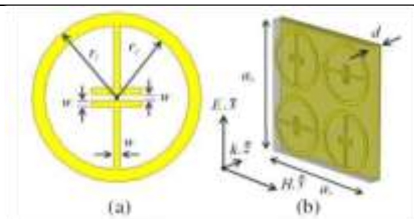
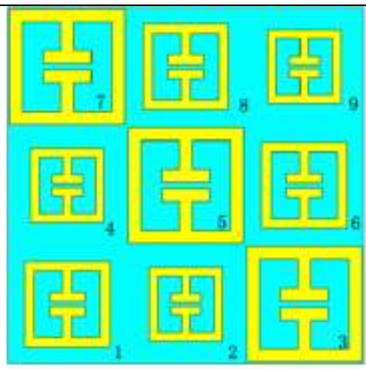
Table 2- 4 highlights the limitations associated with different classes of microwave absorbers.

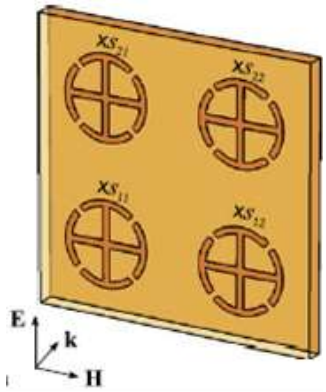
Table 2- 4: Limitations associated with different classes of microwave absorbers

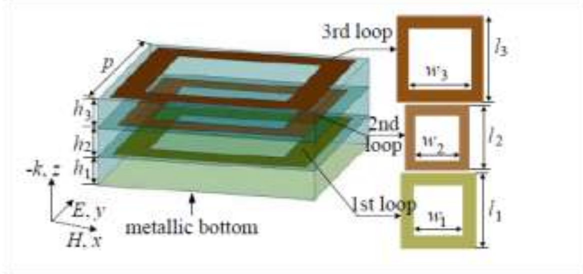
Classical Absorbers	**Material based absorbers**	**Metamaterial Absorbers**
SSMA: Narrow bandwidth and less angular stability, not practical solution for conformal surfaces Jaumann Absorber: large thickness due to multilayer configuration and physical realization and application of customized resistive sheets, not a practical solution for conformal surfaces	The complex chemical synthesis process Health risk due to hazardous chemical Thickness and tuning of constitutive parameters	Very narrow bandwidth due to the formation of resonant RLC circuit Due to the absence of resistive components acts as polarization converter, i.e. minimum reflection in co-polarization and highly reflecting in cross-polarization

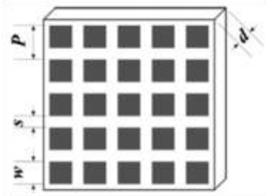
Table 2- 5 presents a brief account of the reported techniques for bandwidth-enhanced absorbers using engineered planar structure.

Table 2- 5: Bandwidth enhancement using engineered planar structures

Methods for bandwidth enhancement	**Reported Literature**
Multiple geometries in the unit cell	 [*Source:* Li *et al.*, 2010]
Scalability of unit cell geometry	 [*Source:* Li *et al.*, 2011]

<table>
<tr><td>Overlapping of resonance modes</td><td>

[Source: Dimitriadis et al., 2012]</td></tr>
<tr><td>Scaling of the unit cell: Multiplayer approach</td><td>

[Source: Yang et al., 2013]</td></tr>
<tr><td>Resistive inks/sheet</td><td>

[Pang et al, 2011]</td></tr>
</table>

The bandwidth of existing absorbers is limited because of the limited tuning of design parameters. The bandwidth improvement techniques require an additional resonance mode. The engineered planar structures are a promising candidate for bandwidth enhancement of the microwave absorbers in terms of ease of fabrication, analysis and tuning of the resonant frequency. The objective of the thesis work is to explore, design, fabricate and characterize simple design methodologies which can improve the bandwidth for -10 dB reflection of the existing absorbers using engineered planar structures.

…