5: Salisbury Screen with Engineered Square Patch and Wire Element

Salisbury Screen Microwave Absorber (SSMA) is the simplest microwave absorber consisting of the resistive sheet placed on the quarter-wavelength thick metal back dielectric spacer. The bandwidth of the SSMA depends on the spacer permittivity. More specifically, the maximum bandwidth of the SSMA can be achieved for a spacer with low permittivity with the penalty of large thickness. The increase in permittivity minimizes the thickness requirement with lower bandwidth. The chapter presents the design methodology using engineered planar structures viz. square patch and wire element to improve the bandwidth of the SSMA.

5.1 SQUARE PATCH SSMA

Theoretically, the maximum fractional bandwidth of the SSMA using FR4 substrate with an optimum sheet resistivity of 308 Ω/sq for -10 dB reflection is approximately 42.1%. In comparison, the bandwidth for square patch-based SSMA is 59.7% with the same thickness. The design comprises of square patches of the SSMA placed periodically on the metal sheet. The square patches consist of FR4 substrate and a 200 Ω/sq resistive sheet. A single reflection minima is observed in the SSMA due to $\lambda/4$ resonance whereas in the proposed absorber an additional resonant mode introduced due to the coupling between the nearby patches. The overlapping of the $\lambda/4$ mode and the additional coupling mode result in bandwidth improvement.

The maximum fractional bandwidth for the SSMA using 3.2 mm thick FR4 substrate with optimum resistivity for -10 dB reflection is 4.7 GHz (8.8 GHz -13.5 GHz). In comparison to SSMA, the simulated and experimental bandwidth for -10 dB reflection is 8 GHz (9.4 GHz-17.4 GHz) for the proposed square patch-based SSMA. The design comprises of square patches of SSMA placed periodically on the metal plate. The square patches are physically realized as 3.2mm thick FR4 substrate with 200 Ω/sq resistive sheet. The good agreement between the simulation and measured data support the design methodology.

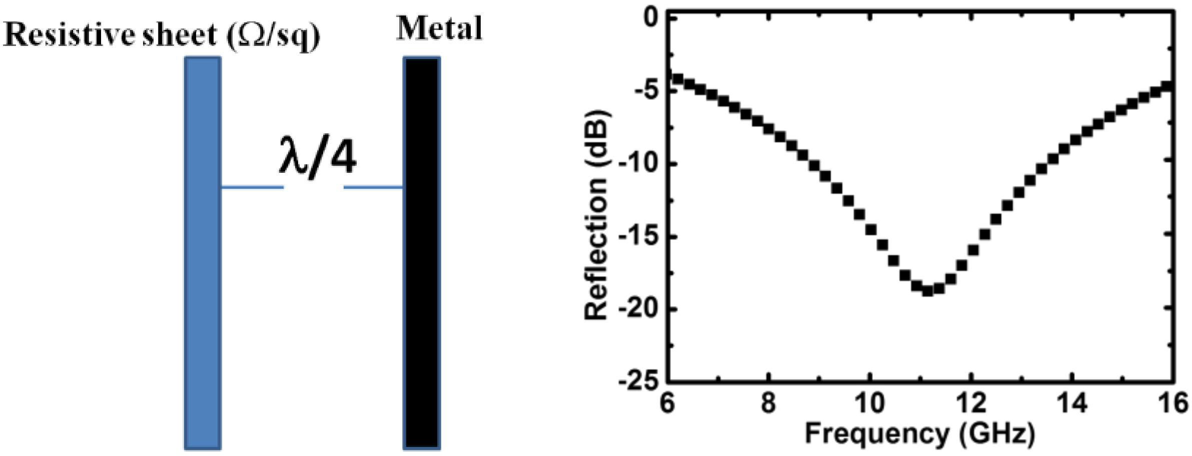
The commercial EM solver viz. CST Microwave Studio is utilized to simulate the S-parameters of the absorbers using frequency-domain solver under unit cell boundary conditions. The field quantities are as well numerically plotted to present the physical insight of the absorber. The performance of the absorber is analyzed for the various angle of incidence under TE and TM modes. The absorbance of the metal back absorber is represented by $A = 1 - R = 1 - |S_{11}|^2$.

5.1.1 SSMA Design

The SSMA is passive microwave absorber used for minimizing the backscatter from the metal. It is constructed of the resistive sheet placed $\lambda/4$ distance from the ground metal plate where λ is the wavelength in the medium [Figure 5-1(a)]. For $\lambda/4$ thickness, it forms an open microwave circuit which results in a single reflection minima due to impedance matching condition [Watts Claire *et al.*, 2012]. The detailed analysis of SSMA is reported in [Chambers, 1994]. The sheet resistivity for maximum absorbance and central frequency are expressed as:-

$$R_s = Z_0\left(\frac{1-\rho\rho^*}{1+\rho\rho^*}\right), \quad f_c = \frac{c}{4d\sqrt{\epsilon}}$$

where d and ε are the thickness and permittivity of the substrate respectively, Z_0 free space impedance, ρ complex reflection coefficient. The optimized sheet resistivity for -10 dB reflection is 308 Ω/ sq. The central frequency of the SSMA can be tuned either by the thickness or the permittivity of the substrate.



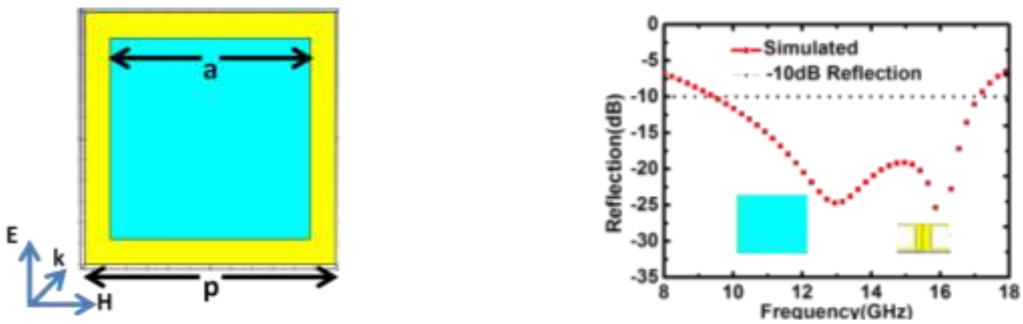
(a) (b)

Figure 5-1: (a) Schematic of the SSMA (b) Simulated reflection of the SSMA for d = 3.2 mm and Rs = 308 Ω/sq

The simulated reflection of the SSMA for sheet resistivity (-10dB reflection) is shown in Figure 5-1(b) which shows the bandwidth of almost 42.1% (8.8 GHz-13.5 GHz) for -10dB reflection. The maximum theoretical bandwidth of SSMA is nearly 76.5% for ε (permittivity)=1 with the penalty of large thickness. Further, the increased permittivity values minimized the thickness with the penalty of narrow bandwidth [Chambers, 1994]. Considering these limitations, it is required to develop an alternative design approach to extend the bandwidth of the SSMA without increasing the thickness of the SSMA.

5.1.2 SSMA With Square Patch

The enlarged top view of the unit cell and simulated reflection of the proposed absorber are shown in Figure 5-2(a) and (b) respectively. The unit cell consists of, bottom to top, metal plate, square patch of FR4 substrate with a resistive sheet of 200 Ω/sq. The dimension of unit cell are; p = 12mm (periodicity), a = 10mm (square patch size), d = 3.2mm (thickness of FR4), tres = 0.13mm (thickness of resistive sheet). The permittivity and dielectric loss tangent of FR4 are 4.2 and 0.02, respectively. The simulated reflection indicates that the reflection is below -10 dB for frequency range 9.4 GHz to 17.4 GHz (Figure 5-2(b)) with a bandwidth of 8 GHz. The total thickness of the absorber is 3.33 mm.

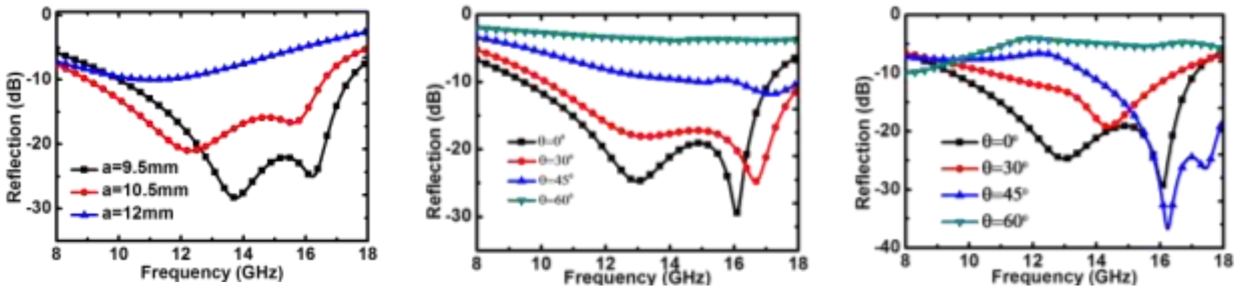


(a) (b)

Figure 5-2: (a) Enlarged top view of the unit cell of the proposed absorber along with field directions (b) Simulated reflection for d = 3.2 mm, Rs = 200 Ω/sq, p = 12 mm and a = 10 mm

5.1.3 Analysis: Square Patch Size Variation

Two reflection minimas are noted in proposed absorber around at 13 GHz and 16 GHz, as shown in Figure 5-2(b). The parametric analysis of patch size indicates that the minima correspond to 13 GHz are attributed to the SSMA whereas the absorption peak at 16 GHz is due to capacitive coupling between the nearby square patches [Costa *et al.*, 2010]. As the patch size increases, the reflection minima (16 GHz) shifts towards lower frequency region due to the increased coupling strength (Figure 5-3(a)) [Costa *et al.*, 2010]. For the given material, the coupling strength depends on patch size and spacing between the patch [Luukkonen *et al.*, 2009]. The square patches reduce the SSMA impedance, which results in shifting of the SSMA absorbing peak (corresponding to 13 GHz) to higher frequency region (Figure 5-3(a)). The two reflection minima are selectively overlapped for a=10mm (square patch size) and result in 8 GHz bandwidth for -10 dB reflection (Figure 5-2(b)). For a=12mm=p, the space between the patches is zero, which vanishes the coupling between the patches and results in the single resonant mode as observed in SSMA (Figure 5-3(a)).



(a) (b) (c)

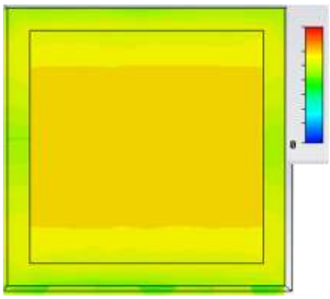
Figure 5-3: (a) Simulated reflection for different patch size (b) and (c) Simulated reflection for a different angle of incidence TE and TM modes respectively

5.1.4 *Analysis: Oblique Angular Stability*

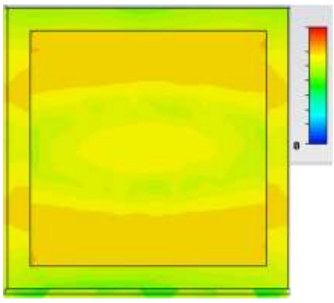
The simulated reflections of the absorber for a different angle of incidence are shown in Figure 5-3(b) and (c) for TE and TM modes, respectively. The orientation of the absorber under TE and TM modes for a different angle of incidence is discussed in [Bhattacharyya, 2016]. The performance of the absorber under TE and TM modes is stable up to an angle of incidence 30^{o} and normal incidence, respectively. The less angular stability of the absorber under TM mode is attributed to variation in resistivity of the resistive sheet [Chambers, 1994]. The multilayer configurations are designed to achieve almost equal bandwidth under both polarizations [Chambers, 1994].

5.1.5 Analysis: Physical Insight

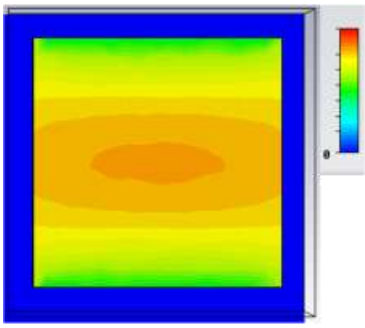
The field quantities are plotted at 13 GHz and 16 GHz to present the physical insight of the absorber (Figure 5-4). The electric field at 13 GHz is confined at resistive sheet whereas, at 16 GHz, it is maximum at the edges of the square patches. The large electric field at edges indicates the presence of electric charges which leads to the formation of the capacitive feature. The power loss distribution at 13 GHz indicates the maximum power loss is attributed to the resistive sheet, whereas 16 GHz the power loss is confined to the edges of the square patch. The field quantities support the origin of additional resonance mode due to capacitive coupling between the patches.



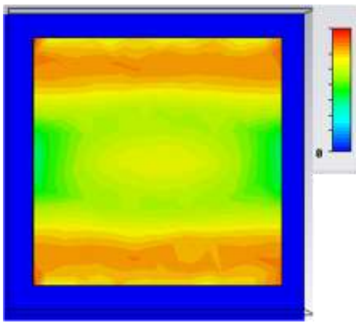
(a)



(b)



(c)



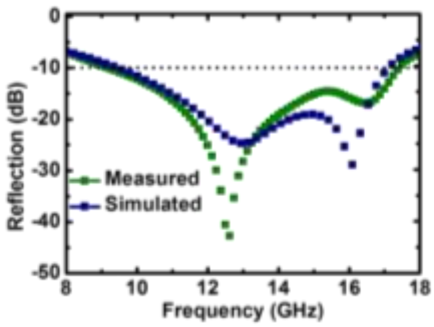
(d)

Figure 5-4: Simulated field quantities at 13 GHz and 16 GHz for p=12mm, a=10mm, d=3.2mm (a) and (b) Electric field at 13 GHz and 16 GHz respectively (c) and (d) Power loss density at 13

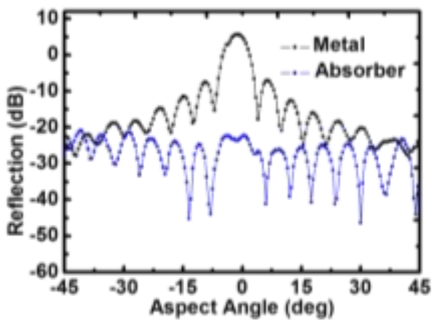
5.1.6 Fabrication and Measurement

For demonstration purpose, the absorber is fabricated (Figure 5-5(a)) with the dimension of 120 x 120 x 3.33 mm. The FR4 sheet of thickness 3.2mm with a resistive sheet with resistivity 200 Ω/sq are cut into 10 x 10 mm square patches manually. The patches are placed manually on the metal sheet with the periodicity of 12mm, with epoxy-based adhesive. The performance of absorber is measured in an anechoic chamber using VNA and pair of horn antennas [Li *et al.*, 2010]. The good degree of correlation is observed between the simulated and measured data (Figure 5-5 (b)). The slight deviation is attributed to the non-uniform spacing between the patches due to manual alignment. The reflection from the absorber is measured for different aspect angle (-45^{o} to 45^{o}) and compared with metal at 13 GHz (Figure 5-5(c)). The absorber efficiently reduces the reflection in comparison to metal for every aspect angle. The reduced reflection is attributed to the absorption of the incident wave by the absorber. The performance of absorber is stable up to 30^{o} for -10 dB reflection.

(a)



(b)



(c)

Figure 5-5: (a) Fabricated Absorber (b) Simulated and measured reflection (c) Measured reflection from the metal and the absorber at 13 GHz for different aspect angles

The performance of absorber is compared with other states of the art, wideband microwave absorbers in terms of method, thickness and bandwidth for -10 dB reflection, as listed in Table 5-1 The comparison brings out the fact that by using the proposed simple square patch design the bandwidth of SSMA can be improved with almost the same thickness of the SSMA.

Table 5-1: Comparison with reported absorbers

Ref.	METHOD	Bandwidth GHz (-10 dB reflection)	Thickness (mm)
Present work	Square patch-based Salisbury Screen	8 (9.4-17.4)	3.33
[Seman *et al.*, 2011]	Salisbury Screen with FSS	12 (4.6-16.6)	9
[Kim and Byun, 2012]	Salisbury Screen of the lossy dielectric sheet (carbon nanofiber)	3.8	2.5
[Seman *et al.*, 2010]	Salisbury Screen with resistive loaded high impedance ground plane	9 (4.7-13.7)	9
[Seman and Cahill, 2011]	Salisbury Screen with resistive FSS	10.4 (5-15.4)	7.6

In conclusion, the bandwidth of the existing SSMA can be improved using engineered square patches. The bandwidth of the proposed absorber can be further improved by introducing additional resonances viz. designing a unit cell of different material with varying thickness and sheet resistivity.

5.2 SSMA WITH WIRE ELEMENTS

The bandwidth of the existing SSMA can be improved by introducing additional resonance mode using engineered wire element. The absorber comprises of, wire element printed on FR4 substrate, placed on the top of the SSMA. The SSMA consists of 50 Ω/sq resistive sheet placed on the metal-backed dielectric spacer. The theoretical analysis indicates the bandwidth of the SSMA for -10 dB reflection is 42.1% using FR4 as a spacer for the optimum sheet resistivity of 308 Ω/sq. The proposed absorber shows the bandwidth of 53.5% (8.9-15.4 GHz) for -10 dB reflection. The thickness of the absorber is 0.15 λ_L (lowest cut-off frequency for -10 dB reflection). The FR4 substrate with the SSMA works as Jaumann configuration and introduces an additional resonance mode. The selective overlapping of resonant mode excited by wire element and the additional resonance mode enhances the bandwidth of the absorber. The wire metamaterial is physically realized using low-cost screen printing technique.

The performance and tuning of the design parameters of the proposed absorber are carried out in CST Microwave Studio using frequency-domain solver under unit cell boundary conditions. The absorbance of the metal back absorber is given by the expression: $A = 1 - R = 1 - |S_{11}|^2$. The designed absorber is a combination of SS and Wire element. A brief discussion on the design of SS and wire metamaterial absorber is presented to reveal the working of the proposed absorber.

5.2.1 SSMA Design

SSMA is passive microwave absorber which is widely used for minimizing the backscatter from the metal surface [Chambers, 1994], [Saville, 2005][3-4]. It is constructed by placing a resistive sheet quarter wavelength distance from the metal ground plane. For λ/4 (λ is the wavelength in the medium) distance, it is transformed to an open transmission line which results in a reflection minima due to impedance matching condition.

The simulated reflection from the SSMA using FR4 spacer for different sheet resistivity is shown in Figure 5- 6. As the sheet resistivity approaches the free space impedance, a sharp resonance is observed because of impedance matching condition. The wide reflection minima is observed for sheet resistivity 50 Ω/sq. It indicates that its impedance is almost invariant for the wide frequency range.

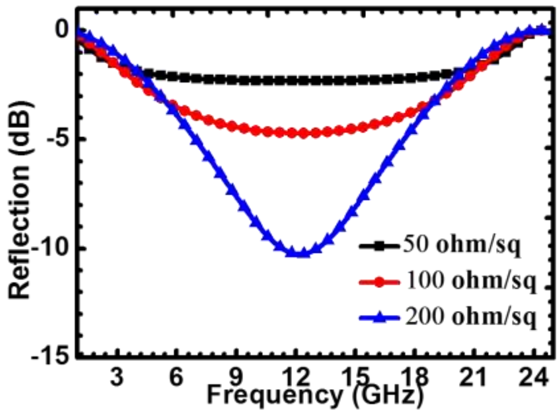


Figure 5- 6: Simulated reflection of SS for Rs = 50, 100, 200 Ω/sq and FR4 (permittivity 4.2 and loss tangent 0.02) spacer thickness = 3.0 mm

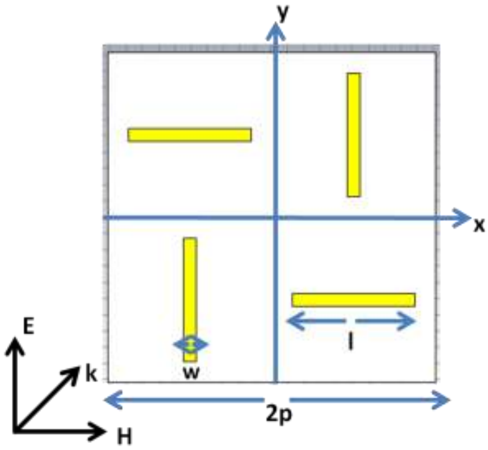
5.2.2 Wire Metamaterial Absorbers (WMA)

The WMA provides flexibility in terms of ease of fabrication, tuning of the resonant frequency and reduced cross-polarization reflection. The detailed analysis of the WMA, along with equivalent circuit modelling, is reported in [Pang *et al.*, 2013]. The resonant frequency of the WMA for the given dielectric substrate is approximated by the expression:-

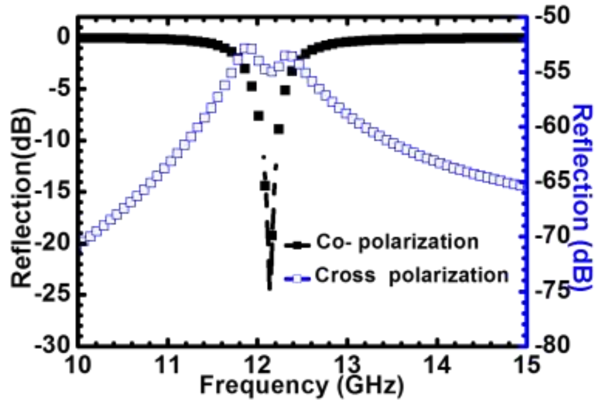
$$f \sim \frac{c}{\sqrt{\varepsilon} l}$$

where c is the speed of the light, ε is the permittivity of the substrate and l is the length of wire element. The resonant frequency varies inversely to the length of the wire element. The additional advantage of WMA is its ability to reduce cross-polarization reflection. The reduced cross-polarization reflection is attributed to the dipole nature of the wire elements.

The front view of a unit cell of the WMA along with field directions and wave vector is shown in Figure 5- 7(a). The unit cell of WMA consists of single wires arranged in horizontal and vertical directions. The dimensions of unit cell are referred as p (periodicity of unit cell) =10mm, l (length of wire elements) = 6.0mm, w (width of wire element) = 0.8mm, for (thickness of FR4 sheet) = 1.0mm. The conductivity and thickness of copper wire are 5.8 x 10^7 S/m and 0.035 mm, respectively. The numerical results indicate the narrow bandwidth for co-polarization due to the resonating structure (Figure 5- 7(b)). The simulated reflection for cross-polarization is below -50 dB, which is almost nil (Figure 5- 7(b)). The WMA can be considered as an efficient absorber which suffers from the narrow absorption bandwidth.



(a)



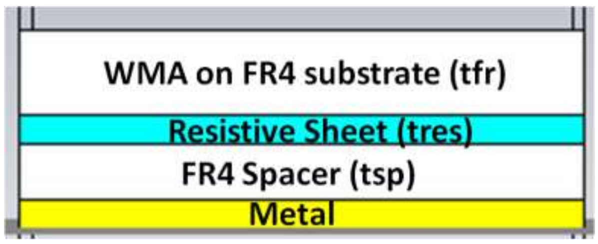
(b)

Figure 5- 7: (a) Front View of WMA (b) Simulated reflection in Co and Cross polarization of the WMA for p = 10 mm, tfr = 1 mm, l = 6 mm, w = 0.8 mm

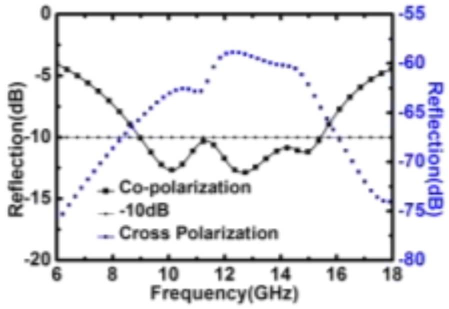
5.2.3 Proposed Absorber

The enlarged side view of the unit cell of the proposed absorber is shown in Figure 5-8(a). The proposed absorber comprises of, bottom to top, a metal plate, dielectric spacer (FR4), 50 Ω/sq resistive sheet and Wire Metamaterial printed on FR4 substrate.

The spacer thickness and sheet resistivity are tuned for maximum bandwidth for -10 dB reflection. The optimized values of sheet resistivity and spacer thickness are 50Ω/sq and 2.0 mm, respectively. The numerically estimated reflections are shown in Figure 5-8(b) for Co and Cross polarization. The proposed absorber indicates the bandwidth of 6.5 GHz (8.9 to 15.4 GHz) for -10 dB reflection. The reflection under cross-polarization is below the -55 dB, which is almost nil. The designed absorber indicates the reduced reflection in co and cross polarizations. The reduced reflection in both the polarizations suggests that the incident wave is absorbed by the absorber.



(a)



(b)

Figure 5-8: (a) Enlarged side view of the unit cell of the absorber and (b) Simulated reflection in Co and Cross polarization of the proposed absorber for p=10mm, l=5.5mm, w= 0.8mm, tfr=3.0mm, tsp=2.0mm, tres=0.1mm and Rs=50Ω/sq

5.2.4 Parametric Analysis: Wire length

The two reflection minima are observed at frequency 10 GHz and 13 GHz (Figure 5-8(b)) The parametric analysis of dimensional parameters and field quantities are numerically estimated at absorbing frequencies to reveal the origin of these absorbing peaks.

It is evident from Figure 5-9 that as the wire length increases the minima corresponds to 10 GHz moves towards the lower frequency. It is attributed to the inverse relation between the wire length and resonant frequency [Pang *et al.*, 2013]. The absorption peak at 13 GHz is almost invariant due to no change in the thickness of FR4 substrate.

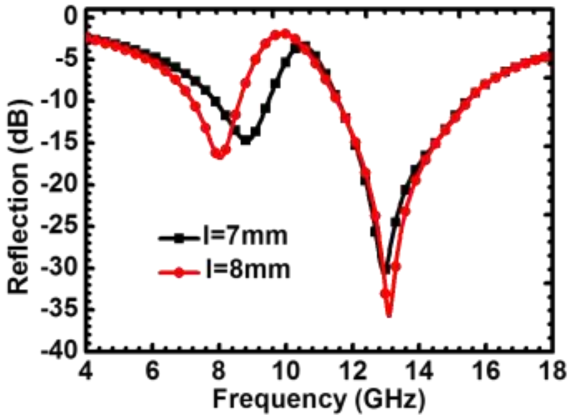
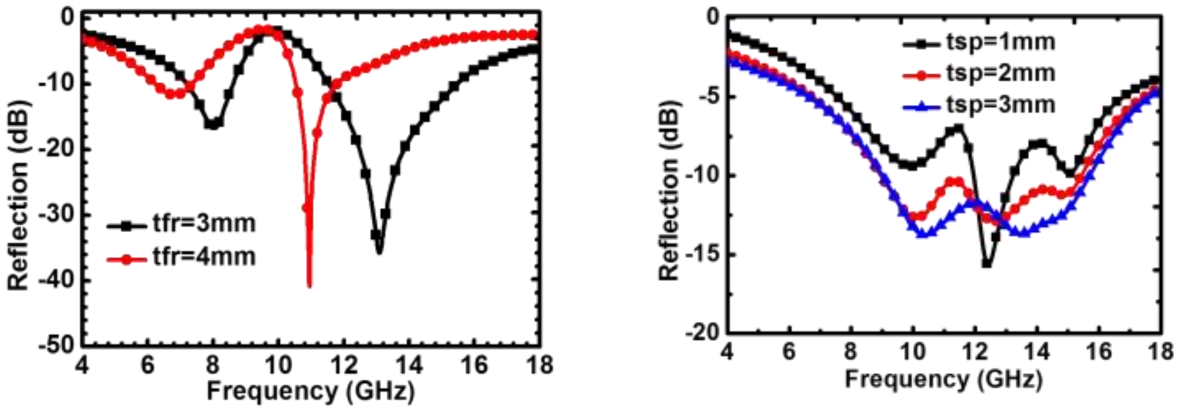


Figure 5-9: Simulated reflection of the absorber for the wire length (l=7 and 8 mm), p = 10 mm, w = 0.8 mm, tfr=3.0 mm, tres = 2.0 mm and Rs = 50Ω/sq

5.2.5 Parametric Analysis: FR4 Substrate

It is noted from Figure 5-10(a) that as the thickness of FR4 substrate increases the resonant mode corresponds to 13 GHz shifts to lower frequency region. This is attributed to the formation of the Jaumann configuration [Chambers and Tennant, 1994]. The FR4 substrate on Salisbury Screen works as the Jaumann configuration. The wire element peak as well as shifts towards the lower frequency. The shift is attributed to the increased inductance of resonating structure of the wire metamaterial absorber ($L\sim\mu ld/w$) [Pang *et al*, 2013].



(a) (b)

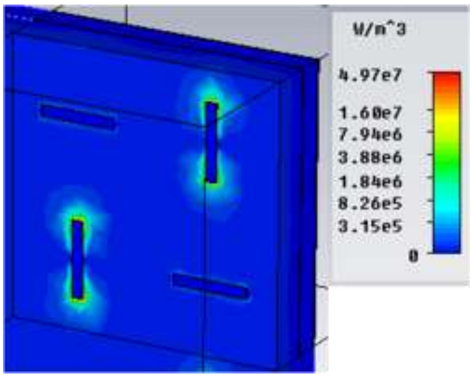
Figure 5-10: (a) Simulated reflection of the absorber for FR4 substrate thickness (tfr = 3 and 4 mm), l = 8 mm, tsp = 2 mm and Rs = 50Ω/sq and (b) Simulated reflection of the absorber for FR4 spacer thicknesses (tsp=1, 2 and 3mm), tfr = 3.0 mm, l = 5.5 mm, Rs = 50Ω/sq

5.2.6 Parametric Analysis: FR4 Spacer

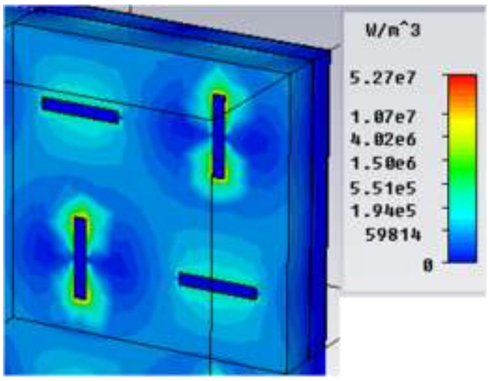
It is noted that as the spacer thickness increases the reflection minimizes, which results in maximizing the absorption (Figure 5-10(b)). It can be attributed to attenuation of the incident wave due to large thickness. The spacer thickness (tsp) is tuned for -10 dB reflection, which is 2.0mm. The further increase in spacer thickness minimizes the reflection with the penalty of the increased thickness.

5.2.7 Physical Insight: Field Quantities

The power loss density of the absorber is calculated at 10 GHz and 13 GHz, as shown in Figure 5-11. At 10 GHz, the power loss distribution is mainly at vertical wires due to the dipole nature of the wire element. The power loss distribution at 13 GHz is confined in the FR4 substrate of wire metamaterial due to the formation of Jaumann configuration.



(a) Power loss at 10 GHz



(b)Power loss at 13 GHz

Figure 5-11: Simulated power loss density for p = 10 mm, l = 5.5, tfr = 3.0 mm, tres = 0.1 mm, tsp = 2.0 mm

5.2.8 Fabrication And Experimental Results

For the experimental purpose and support the design approach, the two absorbers are fabricated with different design parameters, using the low-cost screen printing technique as shown in Figure 5-12 The dimensions of fabricated absorbers are 124 mm x 124 mm x 5.1mm (p=10mm, l=5.5mm, w=0.8mm, Rs=50Ω/sq, tsp=2mm, tres=0.1mm and tfr=3.0mm) and 150 mm x150 mm x 5.8 mm (p=10mm, l=8mm, w=0.8mm, Rs=50Ω/sq tsp=1.5mm, tres=0.1mm and tfr=4.2mm) respectively. The increased thicknesses of the FR4 substrates are physically realized by joining FR4 sheets of different thicknesses using epoxy based glue. The performance of the fabricated absorbers was measured in an anechoic chamber using vector network analyzer and horn antennas as described in [Cheng and Yang, 2010], [Huang and Chen, 2011].

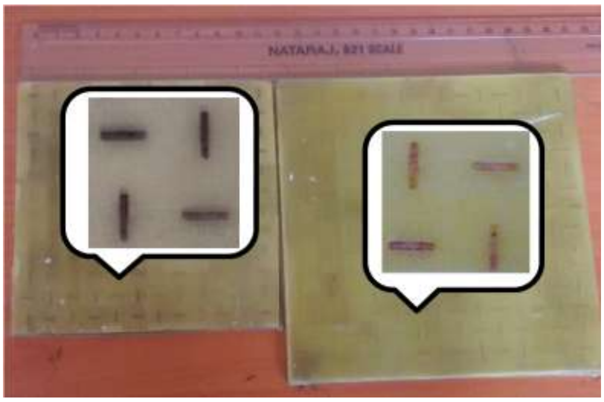
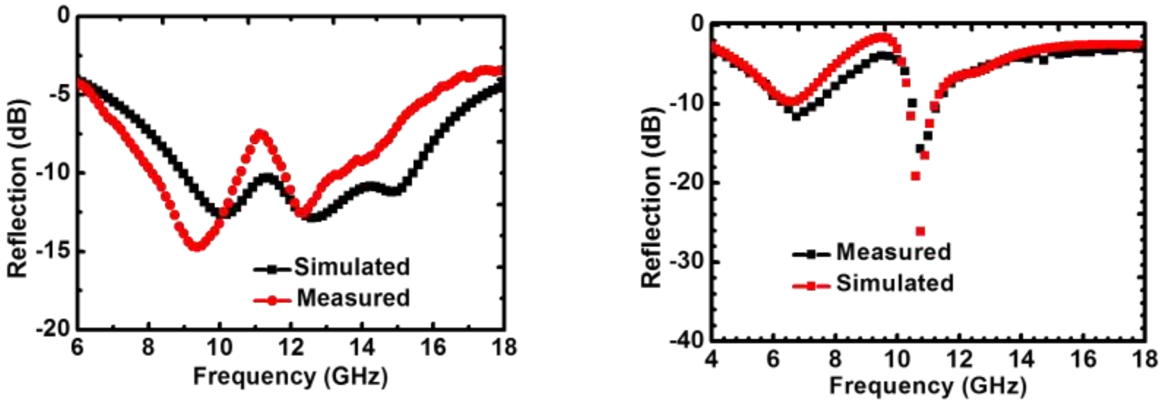


Figure 5-12: Fabricated absorbers using low-cost screen printing technique with p=10mm, l = 5.5mm, w=0.8mm, tfr = 3.0mm, tsp =2.0mm, Rs=50 ohm/sq and p=10mm, l = 8mm, w=0.8mm, tfr = 4.2mm, tsp =1.5mm, Rs=50 ohm/sq

The good degree of correlation is observed between the simulated and experimental data. The slight deviation is attributed to thickness variation of FR4 substrate due to the joining of different FR4 sheets, as shown in Figure 5-13.



(a)(tfr=3.0mm) (b) (tfr=4.2mm)

Figure 5-13: Simulated and experimental data for (a) p=10mm, l = 5.5mm, w=0.8mm, tfr = 3.0mm, tsp =2.0mm, Rs=50 ohm/sq (b) p=10mm, l = 8mm, w=0.8mm, tfr = 4.2mm, tsp =1.5mm, Rs=50 ohm/sq

The performance of the absorber is compared with the reported state of the art broadband absorbers in terms of method, thickness and bandwidth for -10 dB reflection, as listed Table 5-2. The absorber is thinner in comparison to [Seman *et al.*, 2011], [Seman and Cahill, 2011], [Yoo and Lim, 2014] and [Zhi Cheng *et al.*, 2012] and wideband to [Zhi Cheng *et al.*, 2012].

Table 5- 2: Comparison with reported absorbers

Ref.	Method	Thickness (mm)	Bandwidth (GHz) for -10 dB
This work	Salisbury Screen with wire metamaterial	5.1	6.5 (8.9-15.4)
[Ding *et al.*, 2012]	A periodic array of metal-dielectric multilayered pyramids	5	6.9 (7.8–14.7)
[Seman *et al*, 2011]	Salisbury Screen using FSS	9	10 (4.6-16.6)
[Seman and Cahill, 2011]	Salisbury Screen Resistively Loaded FSS	7.6	10.4 (5-15.4)
[Yoo and Lim, 2014]	Combination of Artificial Impedance Surface (AIS) and Resistor-Capacitor (RC) Layer	5.6	8.17 (6.79–14.96)
[Zhi Cheng *et al*, 2012]	Metamaterial Absorber based on lumped elements	6	2.5 (3.1-5.6)

In summary, the bandwidth of the SSMA using engineered planar wire element. The proposed design is investigated for different wire lengths and FR4 sheet thickness. The parametric analysis indicated that by changing the wire length and FR4 sheet thickness, the response of the proposed absorber could be tuned. The good agreement between the measured and simulated data support the design approach of the absorber. For practical applications, these absorbers should qualify standard mechanical and environmental test parameters.

…