CHAPTER-VII

OUTCOMES AND FUTURE PERSPECTIVES

The essence of the present research work is to encompass wide absorption bandwidth, low profile geometry, flexibility with polarization independent absorption into development of a single EM shielding material. Here, meta-structure absorbers are designed and fabricated with periodic subwavelength structures of high dielectric loss material encapsulated in a low loss matrix to develop the EM shields.

One of the distinguishing features of the work is the use of gel, instead of reported liquid and solid materials, as embedded resonant structures. Slime and DES gel offer high dielectric loss at microwave frequencies, flexibility, light weight, and ease of synthesis which are desired to develop the subwavelength periodic resonators to attenuate the impinging EM wave.

The other important aspect is the choice of matrix material with low dielectric loss which has high tensile strength, withstands high temperature, impermeable to water and inert to external environment to safeguard the embedded gels. Silicone rubber fits into the requirement of the matrix material and provides mechanical support to the MSA.

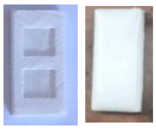
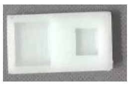
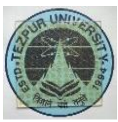
The MSAs are designed using simple symmetric geometries viz. cuboidal with 4-fold symmetry and hexagonal-prism with 6-fold symmetry, for easy fabrication and polarization insensitive absorption. Additive manufacturing technology has been employed to ensure fabrication accuracy and minimize processing time for developing MSAs. Design optimization of the MSAs for obtaining wide-band impedance matching at the air-absorber interface is carried out using CST Studio Suite software which reduces multiple fabrication trials and related cost.

The developed gel subwavelength resonator embedded MSAs successfully substantiates revertibility, RCS reduction and enhancement of antenna isolation.

Optically transparent microwave MSA is developed. The opaque silicone-rubber matrix is replaced with optically transparent urethane rubber, where transparent DES gel is embedded as hexagonal-prism structure. Copper mesh is incorporated as conducting back in place of ITO and graphene to get a flexible, low cost and transparent alternative for a standalone transparent shield. OT-MSA stripped off copper mesh is tested for shielding solar panels. The system showed >10 dB RCS reduction in the entire X-band with 80% relative light conversion efficiency.

Table 7.1 summarizes the specifications of all the gel based MSAs developed and presented in the current dissertation.

Table 7.1 Specifications of the developed gel based MSAs.

MSA	MSAs' Photographs	BW (>90% A_ω) GHz	% coverage of X-band	T mm	ρ ($g\ cm^{-3}$)	P (mm)	WA (%)	P-I range
Slime-based MSA (Chapter II)		8.7-10.7	47	3	~1.6	12	0.6	±90°
Dual resonator -based slime MSAs (Chapter III)		8.2-12.4	100	3	~1.6	24	0.6	±90°
		8.2-12	90	3	~1.6	24	0.6	±90°
DES gel based MSA (Chapter IV)		8.45-12	84.5	2.75	~1.2	L: 8.4, B: 8.2	0.6	±90°
Dumbbell shaped DES gel MSA (Chapter V)		9.06-12.4	~80	2.75	~1.2	L: 18, B: 8.5	0.6	±90°
OT-MSA Cu-mesh OT-MSA (Chapter VI)		8.5-12.4	93	3.35	~1.32	9.6	2.6	±90°
		8.7-12.4	88	3.2	~1.19	9.6	2.6	±90°
Note: T-thickness, ρ-density, P-periodicity, L- length and B- breadth of the MSA, WA- water absorbance, P-I-polarization insensitivity.								

The calculated weight and estimated material cost for the development of a commercial size (30 × 30) cm absorber sheet/tile of all the presented MSAs are placed in table 7.2.

Table 7.2 Weight and material cost of commercial size (30 cm × 30 cm) gel based MSAs.

Chapter No.	MSA	Weight (kg)	Price without reflecting back (INR)	Price with reflecting back (INR)
II	*Slime-based MSA*	0.432	560	897.7
III	*Dual resonator-based slime MSAs*	0.432	582.9	920
IV	*DES gel based MSA*	0.297	827	1164
V	*Dumbbell shaped DES gel MSA*	0.297	835.3	1172.13
VI	*OT-MSA* *Cu-mesh OT-MSA*	0.343 0.397	1241.2 1241.2	1578.34 1879.3
*The price does not include the cost of manufacturing and equipment, manpower and other operational charges.				

The highpoints of the developed MSAs -

- wide -10 dB absorption covering almost the entire X-band.
- low profiled with thickness of <=$\lambda/10$)
- flexible and lightweight
- polarisation insensitive absorption $\pm 90°$
- negligible water retention
- fabricated ease using simple geometrical structures
- revertible with fast performance restoration capability
- sheathed with environmentally inert enclosures
- steady absorption performance over -15 to 65°C
- low RCS

State-of-the-art review

In order to evaluate the salient features and benefits of the developed gel-based absorbers, results are tabulated alongwith similar reviewed state-of-the-art MSAs. Table 7.3 features of similar single structured water based MSAs with developed slime based MSA.

Table 7.3 Present slime MSA with other similar single structured MSAs.

Ref	Material of the resonator	> 90% A_ω bandwidth (GHz)	FBW (%)	Flexible/Rigid	Thickness (mm) (λ_0)
[1]	Liquid-Water	8.96-11.98	28.8	Flexible	3, 0.089λ_0
[2]	Liquid-Water	5.58-24.1	124.7	Rigid	5.6, 0.10λ_0
[3]	Liquid-Water	12-29.6	84.6	Rigid	5.8, 0.232λ_0
[4]	Liquid-Water	7.7-36.8	130.7	Rigid	3.8, 0.09λ_0
Proposed	Gel -Slime	8.7-10.7	20.6	Flexible	3, 0.08λ_0
Note: A_ω-absorption λ_0-lowest operating frequency and FBW- fractional bandwidth.					

The proposed slime based MSA is thin, flexible with advantage of ease of fabrication because of use of gel.

The features of dual slime resonator MSA with other wide band absorbers are placed in Table 7.4.

Table 7.4 Dual resonant structured slime MSAs with similar multi resonant structured MSAs performance.

Ref	-10 dB BW range (GHz)	Fractional BW (%)	Resonator materials	Flexible /Rigid	Performance restoration	Thickness mm (λ_0)	Structure design
[5]	8.2-12.4	40.77	Water	Flexible	Not reported	3 mm ($0.082\lambda_0$)	Co-planar
[6]	7.6-18	81.25	Graphite SLS	Rigid	-	5 mm ($0.13\lambda_0$)	Stacked
[7]	7-40, 75-110	140.4, 37.8	CC/Wax	Rigid	-	11 mm ($0.262\lambda_0$)	Stacked
[8]	2-4, 8-40	66, 133	Carbon composite	Flexible	-	5 mm ($0.033\lambda_0$)	Stacked
[9]	8-18	76.90	Nylon/ carbonyl iron SLS	Rigid	-	2.89 mm ($0.077\lambda_0$)	Stacked
Proposed MSAs	8.2-12.4	40.77	Slime (PVA-borate hydrogel)	Flexible	Revertible	3 mm ($0.082\lambda_0$)	Co-planar
Note: BW- bandwidth and λ_0-lowest operating frequency							

In contrast to stacked resonators in[6, 9], the absorber developed here is made up of co-planar embedded resonators, which give the absorber a planar finish and allow for easy mounting on curved surfaces. Additionally, the embedded structure employed in the present work offers durability to severe environments and reduces installation and fabrication complexity. Moreover, the proposed MSA advantages of being flexible and revertible that may find applications in conformal surfaces.

The RCS performance and other specifications of the DES gel-Si-MSA developed in chapter IV are compared with current similar-state-of-the-art periodic structured absorbers in Table 7.5.

Table 7.5 Single structured DES gel MSA alongwith similar state-of-the-art absorbers.

Ref	P (mm)	Metallic / non-metallic RS	10 dB RCSR dB BW range (GHz)	FBW %	P-I	T mm (λ_0)	Structural strategy	RCSR mechanism	Flexible/ Rigid
[10]	10.2	Metallic	4.77-5.06	5.9	–	0.9 (0.0143λ_0)	Multi-layered	Absorption	Rigid
[11]	11.25	Metallic	6.5-20	101.9	±90°	3.6 (0.078λ_0)	Coded unit cells, multi-layered	Absorption and scattering	Rigid
[12]	10.93	Metallic	13.42-22.66	51.2	±90°	2.87 (0.1284λ_0)	Lumped elements	Absorption	Rigid
Proposed MSA	L: 8.4, B: 8.2	Non-metallic	8.45-12	35	±90°	2.75 (0.0775λ_0)	Single layered, embedded unit cell	Absorption	Flexible

Note: P-period, L- length and B- breadth of MSA RS- resonating frequency, RCSR- radar cross section reduction, BW- bandwidth, FBW- fractional bandwidth, PI- polarization insensitivity and T-thickness ($\boldsymbol{\lambda_0}$- lowest operating frequency).

The DES gel MSA developed here has lower periodicity indicating its effectiveness in reducing RCS for compact systems. The flexible feature gives an edge over rigid absorbers for conformal surface usages. Another attribute of the absorber is its non-metallic embedded structure providing substantial resistance to harsh environmental conditions. Unlike the other reported MMA which uses either multi structural designs or coded multi-unit cells or lumped elements, the proposed structure is co-planar with simple geometric, passive unit cells making it easy to fabricate and is cost effective.

A comparison of structured absorbers, developed exploiting ionic conductivity properties of resonating material is provided in Table 7.6 alongwith the uniquely designed dumbbell shaped DES gel MSA developed in chapter V.

Table 7.6 Performance assessment of dumbbell shaped DES gel MSA alongwith similar state-of-the-art absorbers.

Ref	Ionic Gel/ Liquid	-10 dB BW range (GHz)	FBW (%)	Resonator covered/ Uncovered	Min RL (dB)	T (mm) (λ_0)	Antenna isolation	Flexible/ Rigid
[13]	IL	8.2-12.4	40.7	Covered	-37.7	3.5 (0.0958λ_0)	Not reported	Flexible
[14]	IL	8.2-28.3	110	Uncovered	-37.5	3 (0.822λ_0)	Not reported	Rigid
[15]	IL	9.26-49	136	Covered	-40	4.2 (0.1296λ_0)	Not reported	Rigid
Proposed MSA	Ionic gel	9.05-12.4	31.2	Covered	-40.02	2.75 (0.0753λ_0)	>30 dB	Flexible

Note: BW- bandwidth, FBW- fractional bandwidth, RL- reflection loss, T-thickness and IL- ionic liquid.

Inferring from the Table 7.6, it is apparent that the ionic DES gel MSA in addition to the benefit of gelated resonating material, offers several perks, including high reflection loss at resonance, flexibility, and a relatively low thickness. The dumbbell shaped provides the necessary shape retention and stability to the structure. Furthermore, from the antenna isolation studies, the proposed dumbbell shaped DES gel MSA is expected to find application in enhancing antenna isolation to more than 30 dB in co-sited trans-receiving systems.

Table 7.7 compares the absorption, RCS and optical characteristics of contemporary optically transparent structured absorbers together with the optically transparent DES gel MSA developed in chapter VI.

Table 7.7 Optically transparent DES gel MSAs' characteristics with similar state-of-the-art absorbers.

Ref	A_{ω} ≥90 % BW (GHz)	FBW (%)	10 dB RCSR BW (GHz)	Flexible	T (mm) (λ_0)	P (mm)	Structural design	Specific application	OT (%)
[16]	5.8-12.2	71.1	-	Yes	5	10	Multi-layered	-	62
[17]	11.2-18.2	74.7	11.2-18.2	Not reported	~3.1 ($1.1573\lambda_0$)	7.5	Multi-layered	Solar panel	79.2
[18]	7.82-17.15	74.70	7.82-17.15	Not reported	2.25 ($0.0909\lambda_0$)	15	Multi-layered	Solar panel	55.45
[19]	6.28-14.38	78.4	-	Not reported	5 ($0.173\lambda_0$)	13	Single layered	-	≥ 75
[20]	8-18	76.9	-	Yes	4.5	10	Single layered	-	80.2
Proposed OT-MSA	8.7-12.4	35	8.2-12.4	Yes	3.2 ($0.0875\lambda_0$)	9.6	Single-layered, embedded	Solar panel or any metallic target	80.03
Proposed Cu mesh -OT-MSA	8.5-12.4	37.3	8.2-12.4	Yes	3.35 ($0.0916\lambda_0$)	9.6	Single-layered, embedded	Any non-metallic target.	45.53

The developed optically transparent MSAs are low profiled, flexible, simple and single layered embedded structures with lower periodicity. They exhibit more than 80% optical transparency and effectively camouflage solar panels without compromising on its performance and aesthetics. OT-MSA devoid of mesh and

Copper mesh backed OT-MSA may find numerous applications on both metallic and non-metallic targets.

Future perspectives

The absorber performance of gel based MSAs are constrained with the change in state of the embedded gel with temperature which modifies the material parameter thus effecting the fundamental absorbing conditions. Though performance evaluation of the absorbers has been conducted with varying bending time, a study on the point where the material reaches fatigue and breaking point will provide a more realistic application data. Antenna isolation using developed MSAs is an interesting application. The results presented here are, however, simulated. It will be more useful if isolation measurements could be carried for onsite antenna systems. The reasonably good performance of gel based MSAs are conducted in X-band. The studies can be extended towards the C-band and Ku-band for the 5G applications. In future, performance studies can be conducted in extreme environment conditions such as sudden shocks, under water/saline water, under high pressure and vacuum, at high altitudes and high speeds.

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List of Publications:

Journals:

1. Saikia S. and Bhattacharyya N.S., An X-band meta-structure absorber based on gelated deep eutectic solvent. *Journal of Applied Physics,* 131(22): 224901, (2022).

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2. Saikia S. and Bhattacharyya N.S., RCS reduction using embedded meta-structure absorber in X-band. *Journal of Physics D: Applied*, 56: 375501, (2023).

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3. Saikia, S., H. Saikia, and N.S. Bhattacharyya, Revertible wideband hydrogel-based meta-structure absorber. *Applied Physics A*, 130(3): 1-15, (2024).

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1. Saikia, S. and N.S. Bhattacharyya. Polarization independent meta-structure absorber using array of embedded gelated deep eutectic solvent for X-band applications. In *2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, 2022 pages 1689-1693, 2022. IEEE.

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2. Saikia, S. and N.S. Bhattacharyya. Slime based meta-structure absorber for X-band applications. In *2022 URSI Regional Conference on Radio Science (USRI-RCRS)*, 2022 pages 1-4, 2022. IEEE.

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1. Saikia S. and Bhattacharyya N.S., Periodic enclosed 'Slime' structures as polarization-independent microwave absorber. In *Advances in Physics and Applications*, pages 7-10, ISBN: 978-93-91953-06-5(2020).

2. Saikia S. and Bhattacharyya N.S., A flexible metamaterial-based microwave absorbing tape at X-band. In *Recent trends in Physics*, pages 274-279, ISBN: 978-93-90951-66-6, 2022.

In pipeline for filing patent:

1. Saikia S. and Bhattacharyya N.S., See-through meta-structure absorber for camouflaging solar panel.