Slime based meta-structure absorber for X-band applications

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Abstract

Herein, an X-band meta-structure absorber is proposed with a thickness of 3mm (=$\lambda/10$). The absorber is designed and developed using viscous slime embedded in cuboidal structures made of flexible silicone rubber substrate. The absorber is backed by aluminium tape. The developed absorber shows a reflection loss of – 36.92 dB (>90% absorption) at 9.46 GHz with a -10 dB bandwidth of 2 GHz. In addition, the absorber shows cross-polarization insensitivity.

1. Introduction

Miniaturization and hence close proximity of electronic and wireless systems, are challenged by isolation from electromagnetic interferences (EMI). There is a constant improvisation of electromagnetic (EM) absorbers from thick and rigid to thin and flexible along with considerable bandwidth.

Meta-structure exploits both the structural as well as electromagnetic properties of the composing material to give broadband absorption [1, 2]. Good absorption is shown by water based meta-structure absorbers, where the high dielectric loss of water attenuates the impinging wave [3-5]. Embedded water based meta-structure made the system easy to handle[3-5]. Flexible embedded water based meta-structure is reported in [3, 5]. The developed absorber is robust, light and easy to mount on conformal surfaces. Using water as meta-structure has some inherent difficulties in fabrication and the mechanical stability degrades with bending.

'Slime', a hydrogel composed of PVA-borate cross-linked network in water (90 wt%) [6] is semi-liquid which can be easily shaped into designed meta-structure geometry. With 90% water content the dielectric loss is found to be almost similar to that of water but unlike water, the high viscous slime eases handling during fabrication.

This work proposes a meta-structure absorber (MSA) designed and developed at X-band, using slime embedded in silicone rubber substrate. Silicone rubber is found to be flexible, and hydrophobic along with a high decomposition temperature of about >350˚C [7].

Commercial CST microwave studio suite is used for performing the simulations. Structure of the MSA unit cell is optimized for minimum reflection loss and wide -10 dB bandwidth. Experimental verification is done using waveguide technique.

2. MSA unit cell design and simulation

The proposed MSA is shown in Figure 1(a). Single unit cell, Figure 1(b), consists of a single cuboidal shaped structure of slime enclosed in a silicone rubber matrix. The unit cell structure is simulated using Frequency Domain Solver in CST. Trust Region Framework algorithm is used for structural optimization. The permittivity of silicone rubber and slime was measured and imported to get the final design parameters presented in Table I.

Optimization of the unit cell structural parameters, Figure 1(b)-(c), is carried out to obtain minimum reflection loss at resonance with a broadband absorption in the range of 8.2-12.4 GHz. The EM wave is allowed to incident on the z-axis as shown in Figure 1(d), while the E- field component, and H-field component oscillates on the y-axis and x-axis respectively. Periodic Boundary conditions and a far-field Floquet port are employed.

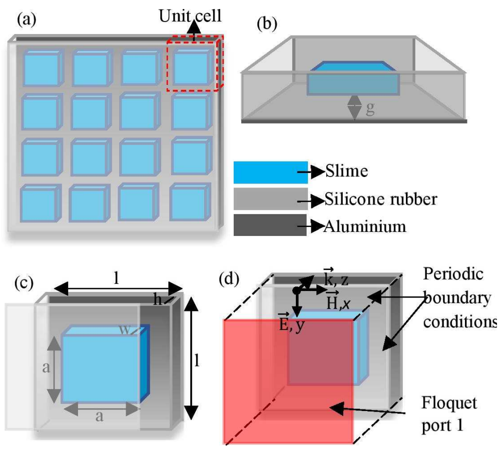

Figure 1. Schematic of (a) proposed slime based MSA, (b) unit cell of the MSA, (c) unit cell parameters and (d) simulation setup.

TABLE I. Optimized parameters of MSA unit cell

Unit cell parameters	Value (mm)
l=length of the cuboid	12.0
h=height of the cuboid	3.0
g=thickness of layer below the slime cuboid	1.0
w=height of the slime cuboid	1.0
a=length of the slime cuboid	7.0

According to the fundamental mathematical expression of absorber, equation (1), unity absorption $A(\omega)$ implies maximum absorption [3-5].

$$A(\omega) = 1 - R(\omega) - T(\omega) \quad (1)$$

Here, transmittance $T(\omega) = |S_{21}|^2 = 0$, since the absorber is metal backed. Now, reducing reflectance $R(\omega) = |S_{11}|^2$ will thus increase the absorption. Impedance matching is done to minimize the reflectance by tailoring effective permittivity (ε_{eff}) and permeability (μ_{eff}) of the material.

The simulated reflection loss (co-polarization or at polarization angle (φ) of 0°) values of the proposed absorber are plotted in Figure 2. The curves show a -36 dB reflection loss at the resonant frequency of 9.65 GHz and 2.01 GHz bandwidth (-10 dB). Using S-parameters normalized impedance can be retrieved as in equation (2) [3-5].

$$Z = \sqrt{\frac{(1+S_{11})^2-(S_{21}^2=0)}{(1-S_{11})^2-(S_{21}^2=0)}} = \sqrt{\frac{(1+S_{11})^2}{(1-S_{11})^2}} \quad (2)$$

When $Z_{real} = 1$ and $Z_{imaginary} = 0$, unity or maximum absorption is achieved. Figure 3 presents the simulated normalized impedance. It can be observed from the figure that the real part approaches unity with value $Z_{real} = 0.96$, while the imaginary part approaches zero with a value $Z_{imaginary} = -0.02$ at the resonant frequency.

Co-polarization and cross-polarization reflection loss terms dependent total absorption of an absorber is given by equation (3) [8, 9].

$$A_{(Total)} = 1 - \left|S_{11(Co)}\right|^2 - \left|S_{11(Cross)}\right|^2 \quad (3)$$

The absorber is simulated to obtain reflection loss for cross-polarization (i.e., at polarization angle (φ) of 90°). Reflection loss characteristics for both the co-polarization and cross-polarization are placed in Figure 4. Both the curves overlap and no variation is observed throughout the X-band range, thus indicating the absorber to be cross-polarization independent. This could have resulted due to the four-fold symmetry of the designed structure.

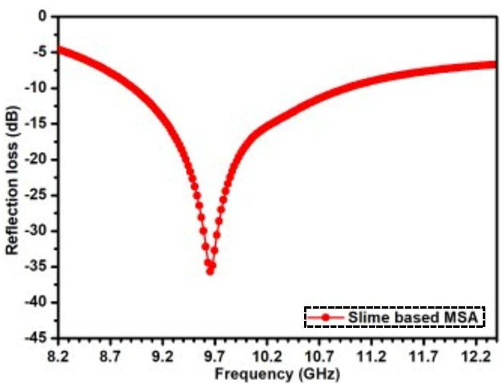

Figure 2. Simulated reflection loss curve.

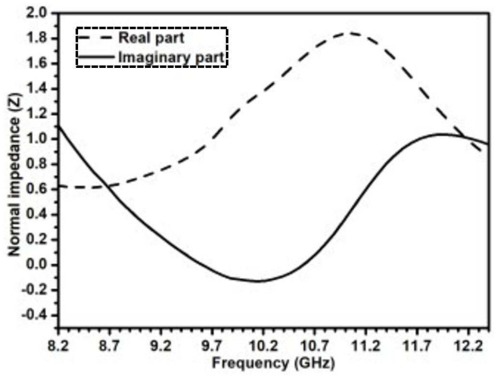

Figure 3. Real and imaginary part of normalized impedance at resonant frequency.

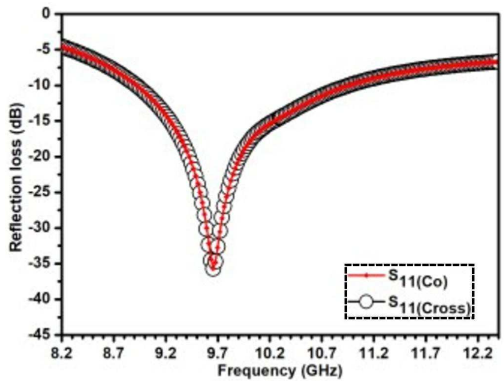

Figure 4. Simulated reflection loss curves of co-polarization and cross polarization terms.

3. Fabrication and measurements

PLA (Polylactic acid) mould of optimized shape and size as in Table I is additively manufactured. Using the PLA mould, silicone rubber substrate is then prepared. Silicone rubber is processed from silicone-RTV viscous gel treated with a curing agent in a 25:1 ratio. The mixture is then poured onto prepared PLA mould and kept undisturbed for 12 hrs. at room temperature. The cuboidal shaped grooves in the silicone substrate are filled with slime which is an optically transparent, semi-solid hydrogel at room temperature. The slime is synthesized by mixing three ingredients- polyvinyl alcohol (PVA with M_w=1,46,000 g/mol), borax (Avantor Performance Materials India Ltd.) and distilled water. 4 wt% of PVA-water is mixed with 4 wt% borax water in a 5:1 ratio through rigorous stirring as in [6]. The permittivity of synthesized slime is measured at X-band using a dielectric probe (Model-N1501A) and analyzed using Vector Network Analyzer (Model-E8362C). The dielectric loss tangent $(\frac{\varepsilon''}{\varepsilon'})$ values are calculated from measured permittivity values and plotted as shown in Figure 5. After filling the grooves, the slime is allowed to take the shape and fit into the silicone rubber enclosures that takes around 1-2 hrs. The surface is

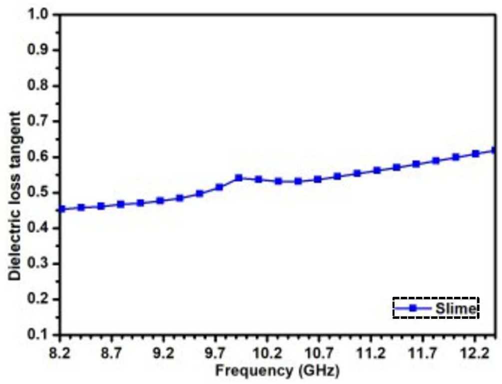

Figure 5. Dielectric loss tangent curve of slime at X-band.

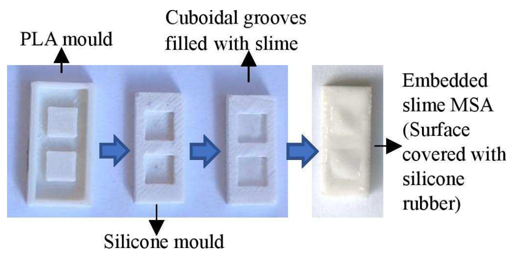

Figure 6. Fabrication of the MSA.

thereafter covered with silicone rubber of 1.0 mm thickness to further protect the slime from evaporation which has low vapour temperature. Finally, the absorber is backed with aluminium tape of thickness ~0.05 mm.

Absorption performance of the developed absorber is recorded using Vector Network Analyzer (Model-E8362). The developed sample is place inside an X-band waveguide kit- Model WR-90X11644A and measurements are taken employing Nicholson-Ross method [10]. The sample is backed with an additional metal short to prevent any leakages of the wave. The reflection loss (S_{11}) is measured via connecting one of the VNA ports to the waveguide setup. Plots of the experimental, as well as simulated reflection loss, are presented in Figure 7. The experimental curve shows a reflection loss of −36.92 dB at 9.46 GHz with a -10 dB bandwidth of 2 GHz. The

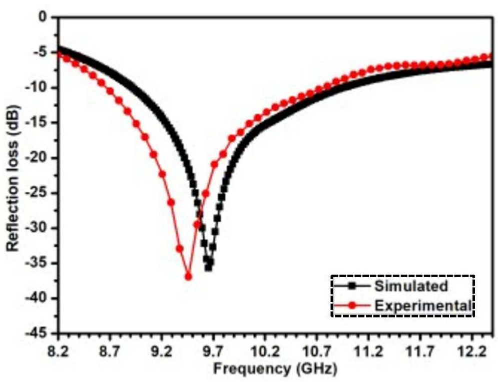

Figure 7. Simulated and experimental reflection loss curves of the slime based MSA.

measured results are observed to be near the simulated results. The minor variation in simulated and measured results may have occurred due to edge diffraction caused by the sample's finite size, additional filling of silicone rubber in the MSA edges to fit the waveguide size, and fabrication tolerance. It is also observed that the embedded slime tends to form a sphere similar to a water droplet on a hydrophobic surface due to the hydrophobicity of silicone and the strong cohesive property of slime. This tendency of slime may have contibuted in the discrepancy between measured and simulated results.

4. Conclusion

A slime based meta-structure absorber is successfully developed and demonstrated. The high dielectric loss tangent of slime assists broadband absorption in the X-band range. Further, replacing embedded water with slime reduces thickness. The absorber is cross-polarization independent due to structural symmetry. The developed absorber shows a reflection loss of −36.92 dB at 9.46 GHz with a -10 dB bandwidth of 2 GHz. Moreover, self-healing property (reforms when contacted after being cut) of slime is advantageous in developing flexible absorber. Finally, the produced paper shows a considerable bandwidth, good absorption (>90%) at the resonant frequency, and flexibility with lightweight features, exhibiting a promising prospect for its use in compact electronics.

5. References

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