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ELECTRICAL CHARACTERIZATION OF GLASS FIBER REINFORCED POLYMER (GFRP) COMPOSITES FOR FUTURE META SURFACE ANTENNA APPLICATIONS

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ABSTRACT: Inthispaper,the GlassFiberReinforcedPolymer(GFRP)compositesamplesareexploredinordertoevaluate their feasibility and adaptability for use in future metasurface antenna application. Multi-layer GFRP composite samples are fabricated with a proportionate ratio of resins and fiber usingVacuumAssistedResinTransferMolding(VARTM)technique.Ntypetowaveguide(WR-187)adapterspeciallydesignedforelectricalcharacterizationoftheseGFRPcompositesamplesisused. Thru-Reflect-Line (TRL) calibration technique is used for the test setup, and scattering parameters oftheseGFRPsamplesismeasuredbyusingthemanufacturedadapteralongwiththesampleholderonatwoportVectorNetworkAnalyzer(VNA).RelativepermittivityanddielectriclosstangentofGFRPcomposite samples are computed using Nicholson-Ross-Weir (NRW) and New Non-Iterativeconversionmethods.Thecomparativeanalysesofbothmethodsshowedaverygoodagreement betweenthem.TheGFRPsamplewiththelowestrelativepermittivityisshortlistedforitspossibleapplicationinfuturemetasurfaceantenna.

Inroduction :

Composite materials have gained popularity over the years, and are being frequently used in differentengineering applications, because of superior advantage over commercially available engineering materials [1].Compositesreinforcedwithfibersofeithersyntheticornaturalmaterialsasdemandforlight weightmaterialaregrowinginthemarket.Fiber reinforcedpolymercompositesnotonlyofferhighstrengthtoweightratiobutalsoprovide good electrical properties, high fracture toughness, durability, excellent corrosion and thermalresistance. Additionally, synthetic fiber in raw form is quite cheaper compared to other commercially availablematerialsinproductforminthemarket [2].Glassfiberisoneofthemostcommonlyused syntheticfiberemployedinwidevarietyofapplications,including but not limited to electronics, mechanical, construction, automotive, aerospace, biomedical andmarine [3–6]. Glass fibers under different class of families (S-glass, E-glass and D-glass etc) are used incombinationwithfillersandpolymermatricestoformcompositeGlassFiberReinforcedPolymer(GFRP).GFRPareusedin differentelectronicapplications, such asterminals, connectors,industrialsandhouseholdplugs,switches,andPrintedCircuitBoard(PCB)etc.Ithas apotentialofusinginthefieldofRF/Microwave. Recently,inthefieldofRF/Microwave,MetamaterialandMetasurfacestructuresaregainingpopularitydue toelectromagneticperformanceenhancement. Metasurfaceistypicallymanufacturedusingasmallsetofscatterersinaregulararraythroughouttheregioninordertoobtaindesirableelectromagneticbehavior.Metasurfacehaswidevarietyofpotentialapplicationsinthefieldofelectromagnetics[7],includinguseofMetasurfacebasedantenna [8].Useof2DMetasurfaceinthefieldofantennaenhancesantennasperformance rangingfromapertureefficiencyimprovement[9],frequencyre-configuration [10],switchablepolarization [11],highgainandwidebandwidth [12–14].Presently, metasurface antenna usesCommercialoff-the-Shelf

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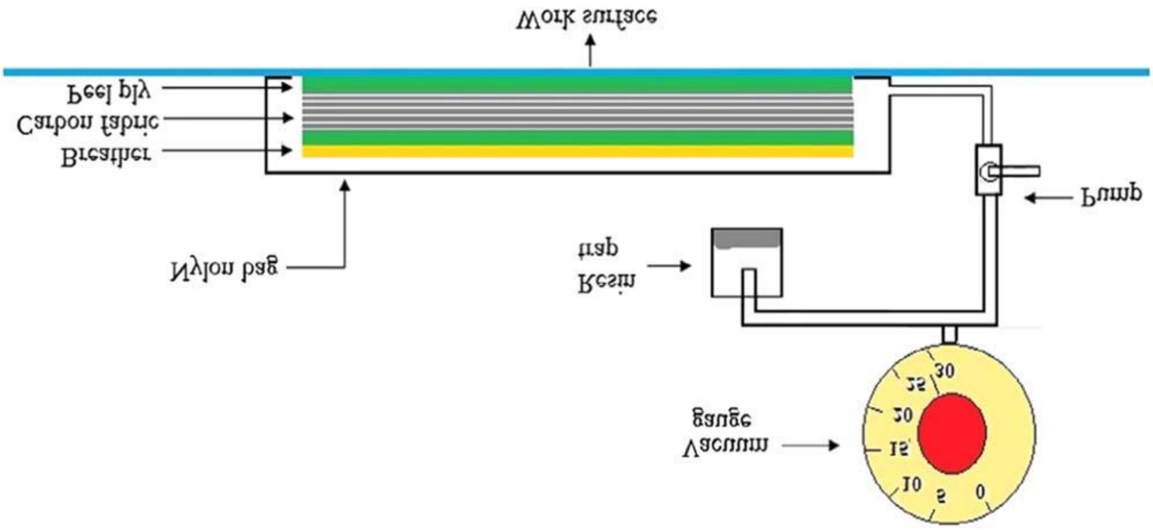
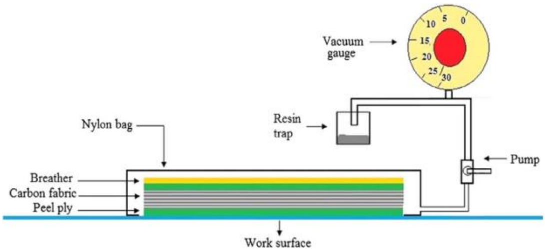
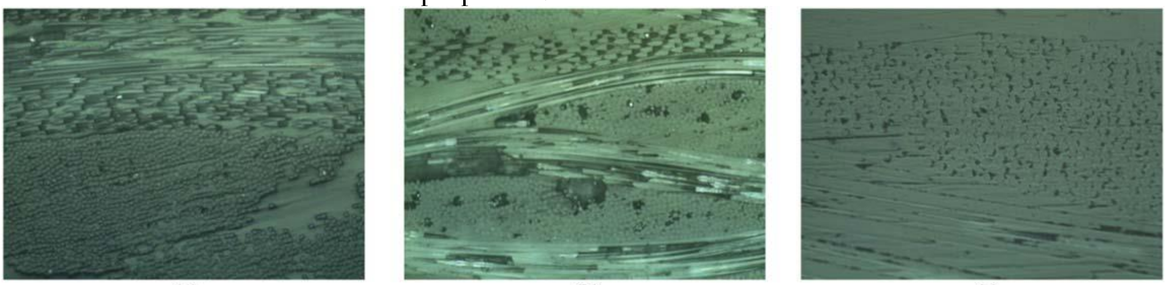




(COTS) based substrates [9–15]. These COTS based substrates are very expensive and can be replaced withGFRP based composite which are not only low cost but also offer good electrical and mechanical properties.

Atfirst,itisimportanttocharacterizeGFRPbasedcompositepolymersfortheirdielectricandmaterial properties.This is critical for the design of Metasurface and antenna structures on them [16]. An important feature of suchcomposite polymers is their ability to modulate their dielectric properties by varying the size, shape andconductivity of the filled constituent used in the polymeric matrix. Thus, the rationale of using GFRP basedpolymersinthedesignofreconfigurableantennas.



(a) (b) (c)

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Table 1. Material composition of composite samples manufactured using VRATM technique.

Sample ID	Sample Image	Material Composition
X		**Reinforcement:** Chopped E-glass fibermat, Density 450 g m^{-2}; sample thickness 2.32 mm. **Matrix:** Thermoset epoxy resin (Bisphenol-A) with hardener (Cycloaliphatic amine), Ratio of epoxy to hardener was kept 10:3.5 by weight. **Number of Layers:** 05 **Make (Matrix):** (Huntsman, Germany)
Y		**Reinforcement:** E-Glass fiber peel ply, Linear Density 200 g m^{-2}; Plain weave, sample thickness 2.62 mm. **Matrix:** Araldite GY 6010 epoxy resin with medium viscosity and high shelf life. **Number of Layers:** 15 **Make (Matrix):** (Huntsman, Germany)
Z		**Reinforcement:** Chopped E-glass fiber mat, Density 450 g m^{-2}, sample thickness 3.20 mm. **Matrix:** Araldite GY 6010 epoxy resin with medium viscosity and high shelf life. **Number of Layers:** 25 **Make (Matrix):** (Huntsman, Germany)

In this paper, manufacturing of GFRP composite samples is done using VARTM technique [21] and scattering parameters of the manufactured samples are measured on a Vector Network Analyzer using TRL method [23]. NRW [24, 25] and new non-iterative conversion methods are used to compute the relative permittivity and dielectric loss tangent of each sample. One of the composite samples with the lowest relative permittivity will be then used for potential usage in metasurface antenna applications. In the past, antenna designers have used COTS based substrates[9–15] as metasurface. In this paper, we propose a novel idea of using an indigenously developed GFRP composite as a metasurface in antenna applications.

2. MANUFACTURING OF GFRP COMPOSITE SAMPLES

Manufacturing of composite samples is done using chopped E-glass fibermat and E-glass fiber peel ply cloth.

Fiber reinforced composite samples are fabricated through VARTM technique. For this purpose, a metallic plate is cleaned with acetone, and wax is applied on it for easy release of the mold after sample curing. Multiple numbers of sheets of glass fabric are stacked upon each other on a metallic plate. Then a polyester peel ply is placed over the layers of glass fabric, and a breather cloth is placed underneath it. An airtight nylon bag is positioned over the entire setup and a vacuum pump is attached to generate a constant vacuum pressure of 0.8 bars for 1 h. Schematic illustration of the VARTM technique is shown in figure 1.

Leaks are checked properly before switching on the vacuum pump. Plastic pipes are used as medium for resin infusion and vacuum generation, while tacky tape is used for mold sealing and vacuum retention purpose.

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After the process, pump is switched off, while keeping the composites under vacuum for sample curing. Several samples with different configurations(change of number of layers and glass fiber) are manufactured. After the detailed scrutiny of all samples, 03 samples(Sample-X, Sample-Y and Sample-Z) of different thickness are short listed and discussed in this paper. All 03 samples are cured by heating the sample 30 min at 80 °C, 30 min at 120 °C and 2 h at 160 °C. Different number of layers is used in each sample resulting in different sample thicknesses. In this manner, the influence of varying number of layers on electromagnetic behavior will be studied in present article. The cured composite samples are removed and cut to desired dimensions for characterization. All samples are fabricated via similar method; however reinforcement and matrix materials are changed according to table 1.

Composite samples(X, Y, Z) are subjected to optical microscopy for microstructural investigation. For optical microscopy, samples are prepared by following the standard grinding and polishing technique to obtain flat smooth surface. Images are captured at ×200 magnification using optical microscope (Optkia, Italy) and representative micrographs are shown in figure 2. As can be seen in the optical micrographs, fibermat and fiber ply are placed in three different orientations(0°, 45°, 90°). Images also illustrate proper manufacturing of samples with no voids and delamination defects. These samples can now be further used for their electrical characterization.

3. ELECTRICAL CHARACTERIZATION OF GFRP COMPOSITE SAMPLES

Manufactured GFRP composite samples are electrically characterized for determination of scattering parameters(S11, S12, S21, S22) using a 2 port Vector Network Analyzer(VNA). Characterization has been performed in C-band, i.e. 5.4 to 5.9 GHz. C-band measurement test components include TRL Reflect standard, TRL Thru standard/sample holder, N type to waveguide adapter(WR-187) and N-type to SMA adapter, as shown in figure 3(b). Sample holder and N-type to Waveguide adapter(WR-187) are specifically designed and fabricated to carry out the testing activity.

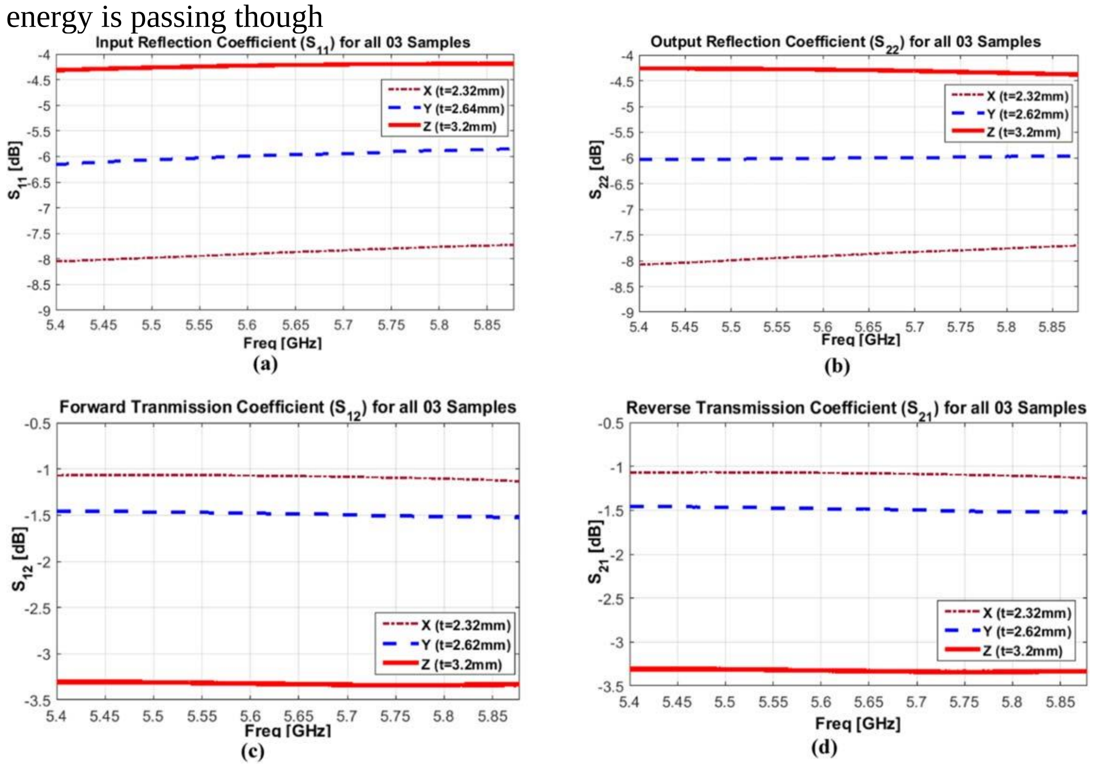
VNA is calibrated before carrying out the measurements, in order to avoid amplitude and phase errors.

Several calibration techniques can be used ranging from TRM (Thru-Reflect-Match), TRL (Thru-Reflect-Line), LRL (Line-Reflect-Line), LRM (Line-Reflect-Match) or SOLT (Short-Open-Line-Transmission). In the current scenario, 2-port Thru-Reflect-Line (TRL) calibration is performed to calibrate the setup in order to avoid any amplitude and phase errors in the measurement data of the samples[27]. After calibration is performed, Sample-Y is fitted in a sample holder as shown in figure 3(a). The sample holder is then sandwiched between the 02 C-band frequency waveguide adapter flanges, as shown in figure 3(c), to measure the scattering parameters.

Measured scattering parameters are saved in touchstone format in order to perform offline post processing, i.e. computing the relative permittivity (εr) and dielectric loss tangent ($\tan\delta$) of the composite samples. Same measurement procedure is repeated for Sample-X and Sample-Z for acquiring the S-parameters.

Scattering parameters of each sample are analyzed to evaluate the manufacturing quality as well as the effect of increasing number of layers from Sample-X to Sample-Z. Figure 4 exhibits plots of scattering parameters for all three samples.

Figures 4(a) and (b) depict measured Reflection Coefficients(S11) at Port 1 and (S22) at Port 2. Both S11 and S22 plots shows similarity for each sample with minimum reflection of energy for Sample-X due to less number of layers(05) and maximum reflection of energy for Sample-Z due to high number of layers(25). Similarity of S11 and S22 plots also indicates that both ends of the surface finish of each sample are smooth with no such perturbations or waviness. Similarly, figures 4(c) and (d) depicts Forward Transmission Coefficient(S12) and Reverse Transmission Coefficient(S21), which shows understandably maximum energy is passing though Sample-X having less number of layers(05), and minimum energy is passing through Sample-Z due to maximum number of layers(25). S12 and S21 plots also show uniform energy power level throughout the frequency band indicating no wavelength of the signal within the band is affected. Smooth scattering parameter plots with no glitches in the complete frequency band indicate proper manufacturing of both composite samples and test adapters. Now we can proceed for the calculation of relative permittivity (εr) and dielectric loss tangent(tanδ).



perturbations or waviness. Similarly, figures 4(c) and (d) depicts Forward Transmission Coefficient(S12) and Reverse Transmission Coefficient(S21), which shows understandably maximum energy is passing though Sample-X having less number of layers(05), and minimum energy is passing through Sample-Z due to maximum number of layers(25). S12 and S21 plots also show uniform energy power level throughout the

frequency band indicating no wavelength of the signal within the band is affected. Smooth scattering parameter
plots with no glitches in the complete frequency band indicate proper manufacturing of both composite samples
and test adapters. Now we can proceed for the calculation of relative permittivity (εr) and dielectric loss
Selection of convergence methods are based on few factors which includes type of measurement method
adopted for calculating the scattering parameters, type of material used, speed and accuracy of convergence
methods. Nicholson-Ross-Weir and New Non-Iterative conversions methods are selected since both methods
supports waveguide based measurements, and are also applicable to planar surfaces with good accuracy of
computing relative permittivity and dielectric loss tangent. Convergence method results are discussed in
upcoming section.

4.1. Nicholson-Ross-Weir(NRW) conversion method

NRW conversion method is the most commonly used conversion method to calculate the relative permittivity
(εr) and permeability (μr) of any material using scattering parameters. NRW conversion method is fast and non
iterative and is applicable to waveguide based measurements performed. In order to calculate the relative
permittivity, Transmission coefficient (T) is calculated using equation (1).

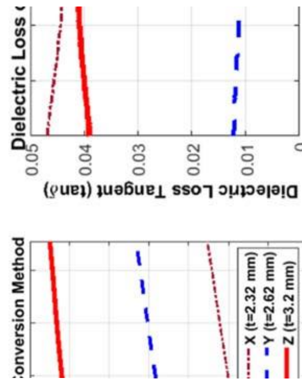
$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}$$

Where, 'Γ' is the reflection coefficient and is calculated using (Γ = X+ *X*2 - 1). MATLAB script of NRW
conversion is written in order to compute the Transmission Coefficient. Relative permittivity is then calculated
using equation (2).

tangent(tanδ)

4. Calculation of permitivitty& dielectric loss tangent of GFRP composite samples

Relative permittivity and dielectric loss tangent of the samples are calculated using two convergence methods.



$$\varepsilon_r = \frac{\lambda_o^2}{\mu_r}\left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi t}\ln\left(\frac{1}{T}\right)\right]\right)$$

Where, 'λ0' is the free space wavelength and 'λc' is the cut off frequency wavelength. WR-187 has an operating
frequency band from 3.95 to 5.85 GHz. Cutoff frequency in this case is considered as 3.95 GHz. 't' is the thickness
of the sample and in this case, all 03 samples tested are of different thicknesses as reported in table 1. Using
equations(1) and (2), relative permittivity (εr) is calculated and reported in figure 5 for all 03 samples.

By analyzing relative permittivity in figure 5(a), Sample-Z with a thickness of 3.2 mm has the highest relative
permittivity throughout the frequency range as compared to Sample-X and Sample-Y. Sample-X with the least
thickness of 2.32 mm as compared to Sample-Y and Sample-Z exhibits the lowest relative permittivity. For
metasurface antenna applications, in which electromagnetic waves needs to radiate, require a surface with the
low permittivity. Results illustrates that Sample-X with 2.32 mm thickness is a suitable candidate compared to

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other 02 samples to be used a metasurface. Thickness of the sample could also have been further reduced in order to further achieve a lower relative permittivity but further reduction of thickness may result in less stiffness and may result in deformation of the sample. NRW conversion method results are validated using New Non Iterative conversion method discussed in the subsequent section.

4.2. New non iterative conversion method

New Non-Iterative method is similar to NRW method but with a different formulation. This method is also suitable for permittivity calculation. This method is fast and non-iterative and no initial guess is needed for relative permittivity calculation. This conversion method also supports waveguide based measurements.

Transmission coefficient 'T' is calculated using equation (1) and relative permittivity is calculated by equation (3).

$$\varepsilon_r = \left[1 - \frac{\lambda_o^2}{\lambda_c^2}\right]\varepsilon_{eff} + \frac{\lambda_o^2}{\lambda_c^2}\frac{1}{\mu_{eff}}$$

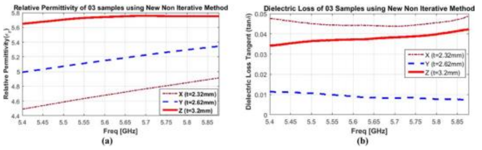
Where, 'εeff' and 'μeff' is the effective permittivity and permeability respectively and is calculated using equations(4) and (5),

Where, 'εeff' and 'μeff' is the effective permittivity and permeability respectively and is calculated using equations(4) and (5),

Where 'Λ' is calculated using equation (6),

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi t}\ln\left(\frac{1}{T}\right)\right]^2$$

Calculated values of εeff, μeffandΛare substituted in equation (3) and relative permittivity is calculated over the complete frequency range. Figure 6 shows the relative permittivity and dielectric loss tangent plots of all 03 samples using New Non-Iterative Conversion method;



(a) (b)

Table 2. Relative Permittivity and Dielectric Loss Tangent of GFRP composite samples.

Sample	Layers (No.)	Thickness (mm)	Frequency (GHz)	Relative Permittivity (ε_r)	Dielectric Loss Tangent (tanδ)
X	5	2.32	5.4 to 5.9	4.5 ~ 4.9	0.042 ~ 0.049
Y	15	2.62		4.83 ~ 5.32	0.008 ~ 0.012
Z	25	3.2		5.35 ~ 5.75	0.035 ~ 0.045

By analyzing the relative permittivity in figure 6(a), similar relative permittivity curves are observed for all 03 samples by using New Non Iterative method in comparison to NRW method. Similarity in computed relative permittivity using both conversion methods indicates that the conversion methods are applicable for this type of waveguide based measurement performed. Plots of relative permittivity for all 03 samples shown in figures 5(a) and 6(a) also indicate relative permittivity value is increasing with the increase of frequency and number of layers in the sample. In order to use a low relative permittivity composite sample for metasurface antenna application [28], based on the findings in this paper, number of fibermat or fiber peel ply layers should be as minimum as possible. Dielectric loss tangent of all the GFRP based composite samples shown in figures 5(b) and 6(b) varies from 0.01 to 0.05 which is in a good agreement with hybrid composites developed using natural fiber[29]. table 2 shows the summarized data of all 03 GFRP composite samples;

By analyzing table 2, Sample-X exhibits lowest permittivity over the complete frequency range as compared to Sample-Y and Sample-Z. Sample-X having a thickness of 2.32 mm with 05 layers and with a computed relative permittivity (εr) of 4.72 and dielectric loss tangent (tanδ) value of 0.045 at a center frequency of 5.65 GHz is suitable to be used for the design of metasurface antenna.

5. CONCLUSION

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In this paper, fabricated GFRP based composite polymers are evaluated for the feasibility as a metasurface antenna. GFRP using chopped E-Glass fiber mat and E-glass fiber peel ply are fabricated using VARTM technique and then successfully characterized using specially designed test jigs. Relative permittivity and dielectric loss tangent of each sample is successfully calculated with the help of NRW and Non-Iterative conversion method with great similarity of results between both methods. Results of all samples indicates that the sample with less number of layers provides lowest relative permittivity. Finally, Sample-X (Chopped E-Glass Fiber mat)with 05 layers having relative permittivity of 4.72 is selected for use in metasurface antenna applications. Future work involves printing of unit cells on the selected composite sample and then use as a metasurface on a patch antenna resonating in the same frequency band from 5.4 to 5.9 GHz. Goal will be the electromagnetic performance enhancement (bandwidth, gain, frequency reconfiguration) of patch antenna using GFRP based composite as a metasurface.

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