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

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ABSTRACT: In this paper, the Glass Fiber Reinforced Polymer (GFRP) composite samples are explored in order to evaluate 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 using Vacuum Assisted Resin Transfer Molding (VARTM) technique. N-type to waveguide (WR-187) adapters specially designed for electrical characterization of these GFRP composite samples are used. Through-Reflect-Line (TRL) calibration technique is used for the test setup, and scattering parameters of these GFRP samples are measured using the manufactured adapter along with the sample holder on a two-port Vector Network Analyzer (VNA). Relative permittivity and dielectric loss tangent of GFRP composite samples are computed using Nicholson-Ross-Weir (NRW) and New Non-Iterative conversion methods. The comparative analysis of both methods showed a very good agreement between them. The GFRP sample with the lowest relative permittivity is shortlisted for its possible application in future metasurface antenna.

Introduction: Composite materials have gained popularity over the years, and are being frequently used in different engineering applications, because of superior advantage over commercially available engineering materials [1]. Composites reinforced with fibers of either synthetic or natural materials are in demand for lightweight material growing in the market. Fiber reinforced polymer composites not only offer higher strength-to-weight ratio but also provide good electrical properties, high fracture toughness, durability, excellent corrosion and thermal resistance. Additionally, synthetic fiber in raw form is quite cheaper compared to other commercially available materials in product form in the market [2]. Glass fiber is one of the most commonly used synthetic fiber employed in wide variety of applications, including but not limited to electronics, mechanical, construction, automotive, aerospace, biomedical and marine [3-6]. Glass fibers under different class of families (S-glass, E-glass and D-glass etc) are used in combination with fillers and polymer matrix to form composite Glass Fiber Reinforced Polymer (GFRP). GFRP are used in different electronic applications, such as terminals, connectors, industries and household plugs, switches, and Printed Circuit Board (PCB) etc. It has potential for using in the field of RF/Microwave. Recently, in the field of RF/Microwave, Metamaterial and Metasurface structures are gaining popularity due to electromagnetic performance enhancement. Metasurface typically manufactured using an all set of scatterers in a regular array throughout the region in the field to obtain desirable electromagnetic behavior. Metasurface has a wide variety of potential applications in the field of electromagnetics [7], including use of Metasurface based antenna [8]. Use of 2D Metasurface in the field of antenna enhancement and antenna performance ranging from aperture efficiency improvement [9], frequency configuration [10], switchable polarization [11], high gain and widebandwidth [12-14]. Presently, metasurface antenna uses Commercial off-the-Shelf
(COTS) based substrates [9–15]. These COTS based substrates are very expensive and can be replaced with GFRP based composite which are not only low cost but also offer good electrical and mechanical properties.

At first, it is important to characterize GFRP based composite polymers for their dielectric and material properties. This is critical for the design of Metasurface and antenna structures on them [16]. An important feature of such composite polymers is their ability to modulate their dielectric properties by varying the size, shape and conductivity of the filled constituent used in the polymeric matrix. Thus, the rationale of using GFRP based polymers in the design of reconfigurable antennas.
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 fiber mat 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.
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, fiber mat 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 (tanδ) 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 through 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).
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4. Calculation of permittivity & dielectric loss tangent of GFRP composite samples
Relative permittivity and dielectric loss tangent of the samples are calculated using two convergence methods.

\[ \varepsilon_r = \frac{\lambda_0^2}{\mu_r} \left( \frac{1}{\lambda_c} - \frac{1}{2\pi t} \ln \left( \frac{1}{\Gamma} \right) \right) \]

Where, ‘\( \lambda_0 \)’ is the free space wavelength and ‘\( \lambda_c \)’ 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
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).

\[ \varepsilon_r = \left[ 1 - \frac{\varepsilon_0}{\varepsilon_{\text{eff}}} \right] + \frac{\varepsilon_0}{\varepsilon_{\text{eff}}} \frac{1}{\varepsilon_{\text{rel}}} \mu_{\text{eff}} \]

Where, ‘\(\varepsilon_{\text{eff}}\)’ and ‘\(\mu_{\text{eff}}\)’ is the effective permittivity and permeability respectively and is calculated using equations(4) and (5), Where, ‘\(\varepsilon_{\text{eff}}\)’ and ‘\(\mu_{\text{eff}}\)’ is the effective permittivity and permeability respectively and is calculated using equations(4) and (5), Where ‘\(\Lambda\)’ is calculated using equation (6),

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

Calculated values of \(\varepsilon_{\text{eff}}, \mu_{\text{eff}}\) and \(\Lambda\) are 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;

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 (\(\varepsilon_r\)) of 4.72 and dielectric loss tangent (\(\tan\delta\)) 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
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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