1. INTRODUCTION

Lightweight materials have become an inevitable requirement for aerospace applications in the form of fuselage, wings, satellite payload, rockets, and so forth. In this class of materials, epoxy/carbon fiber (CF) composites are one of the most preferred materials because of their excellent strength-to-weight ratio, mechanical, thermal and electrical behavior, ease of fabrication, and design. These advantages of epoxy/CF composites can be translated to various high-performance applications. Currently, major components of fighter aircrafts and commercial planes such as fuselage, wings, and so forth consist of CF-reinforced polymers (CFRPs). In addition, they are often used in avionics system, electronics packaging material, optical fiber guidelines, structural applications, robotics, payloads, and so forth and more recently, electromagnetic interference (EMI) shielding application as well. In order to address this issue, we propose thin, lightweight, yet strong epoxy/carbon fiber (CF) composites modified with functionalized graphene oxide (GO) sheets as “interconnects”. This strategy resulted in an impressive 175% improvement in the storage modulus, a 100% enhancement in the lap shear strength, and an extraordinary 200% improvement in the shielding effectiveness at a very low GO content (0.5 wt %). First, GO was functionalized with an epoxy prepolymer (namely E-f-GO) to improve the interfacial adhesion with the matrix polymer, epoxy. As a control, epoxy nanocomposites were also prepared with modified GO. It was followed by the fabrication of CF laminates impregnated with epoxy nanocomposites. Covalent functionalization of epoxy chains on GO sheets was confirmed using various techniques like X-ray diffraction, Raman spectroscopy, Fourier transform infrared spectroscopy, atomic force microscopy, and thermogravimetric analysis. Epoxy nanocomposites were analyzed for thermal, mechanical, electrical, and adhesive strength behavior. CF laminates with epoxy nanocomposites were fabricated using vacuum-assisted resin transfer molding. The E-f-GO/epoxy/CF composite exhibited an excellent shielding effectiveness value of −70 dB, and the storage modulus was found to be >40 GPa. The modified composite showed absorption-driven shielding of EM waves and hence can be used as a highly effective EM absorber.

Polymers have several advantages over metals such as low density, corrosion resistance, ease of processing and molding, and so forth. From the theory of EMI shielding mechanism, we understand that EM waves can be attenuated by three mechanisms, that is, reflection, absorption, and multiple reflections. For an effective EMI shielding behavior, a material should have either charge carriers or magnetic or electric dipoles to attenuate EM waves. Most of the polymers are electrically insulating in nature and do not contain magnetic dipoles; hence, they are transparent to EM waves. Polymers embedded with conducting or magnetic particles can thus be explored for this particular application. Hence, polymer composites can be easily designed to achieve the desired property to counter the issue of EMI shielding materials. Earlier, metals were used to screen devices from electromagnetic (EM) waves, but in the last decade, researchers have switched to polymer composite-based shielding materials. Polymers have several advantages over metals such as low density, corrosion resistance, ease of processing and molding, and so forth. From the theory of EMI shielding mechanism, we understand that EM waves can be attenuated by three mechanisms, that is, reflection, absorption, and multiple reflections. For an effective EMI shielding behavior, a material should have either charge carriers or magnetic or electric dipoles to attenuate EM waves. Most of the polymers are electrically insulating in nature and do not contain magnetic dipoles; hence, they are transparent to EM waves. Polymers embedded with conducting or magnetic particles can thus be explored for this particular application. Hence, polymer composites can be easily designed to achieve the desired property to counter the issue of EMI shielding materials. Earlier, metals were used to screen devices from electromagnetic (EM) waves, but in the last decade, researchers
Apart from electric and magnetic properties, EMI SE of a material also depends on its thickness. There have been several studies which suggest that the shielding efficiency of polymer composites increases with sample thickness.\textsuperscript{21,22}

Epoxy composites have been used in various applications where high mechanical performance is required. However, still efforts are being made to improve the interface between the filler and matrix.\textsuperscript{23–26} It is of great importance to understand the interfacial behavior for aerospace and automotive industry to achieve high strength, high thermal stability, enhanced service life, and ease of manufacturing.\textsuperscript{27–29} Currently epoxy/CF composites constitute a major portion of aircraft and automobiles. However, there have been incidents in the near past, which emphasize to tailor the interface to achieve better EMI shielding performance.

In the present work, we have attempted to develop epoxy composites consisting of graphene oxide (GO) and CF. The objective was to obtain a better interface between the CF and epoxy matrix and hence to translate it into an enhanced mechanical, thermal, EMI shielding behavior. In one of the study, epoxy chains were grafted on a multiwalled carbon nanotube (MWCNT) surface to obtain better dispersion and improved interfacial interactions. Further, epoxy-grafted MWCNT-based composites were prepared, and the effect of surface functionalization on complex permittivity was studied in the frequency range of 1 kHz to 1 MHz.\textsuperscript{30} Kuzhir et al.\textsuperscript{31} studied epoxy composites filled with carbon nanotubes and carbon black for mechanical, thermal, and microwave behavior. In this work, the EMI shielding properties were studied on different epoxy/CF laminates to systematically assess the shielding mechanism as the laminates interact with the incoming EM waves. Our work was mainly focused on the synergistic behavior of functional GO on the mechanical, thermal, and electromagnetic behavior in the frequency range of 12–18 GHz. First, GO was chemically functionalized with an epoxy prepolymer in the presence of a catalyst to tailor the interaction between epoxy and GO.\textsuperscript{32,33} Epoxide prepolymer was selected because of its similar molecular architecture as that of the host matrix. Further, epoxy nanocomposites were prepared with a very low concentration of functionalized GO (0.5 wt %). The modified epoxy nanocomposite was impregnated into a woven CF mat. Epoxy-functionalized GO (E-f-GO) was thoroughly characterized to confirm the chemical reduction of GO using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), Raman spectroscopy, atomic force microscopy (AFM), and thermogravimetric analysis (TGA). Epoxy nanocomposites were prepared with 0.5 wt % of GO and an equivalent amount of E-f-GO using solution method. These nanocomposites were studied to analyze their mechanical, thermal, adhesion, microstructure, and electrical response. After understanding the effect of functionalization of GO on the epoxy matrix, we fabricated CF laminates with epoxy nanocomposites as the matrix. CF laminates were prepared using vacuum-assisted resin transfer molding (VARTM). Further mechanical, electrical, and EMI shielding studies were carried out for E-f-GO/E/CF laminates.

2. EXPERIMENTAL SECTION

2.1. Materials. The epoxy resin (bisphenol-F-epichlorohydrin EPOLAM 8052) and amine-based hardener (2,2′-dimethyl-4,4′-methylene bis(cyclohexylamine)) were kindly provided by Axson Technologies, France. GO was prepared using Hummers method. A polycrylonitrile-based bidirectional woven CF (HCP200A) was procured from Hindoostan Technical Fabrics Limited having a density of 1.8 g/cm\(^3\), with a filament diameter of 7 \(\mu\)m, and an areal weight of fabric 200 gsm. Triphenylphosphine (TPP), catalyst, was commercially obtained. All solvents and reagents used were commercially procured and used without any further purification.

2.2. Synthesis of Epoxy-f-GO. E-f-GO was synthesized using covalent functionalization of GO sheets. The epoxy prepolymer (500 mg) and GO (100 mg) were well-dispersed in dimethylformamide separately using bath sonication. Both solutions were mixed together and stirred for 2 h at room temperature. Further, TPP was added to this reaction mixture as a catalyst, and the reaction was carried out at 100 °C for 24 h. Functionalized GO was washed with acetone thoroughly using the dispersion–filtration–washing method, and finally, E-f-GO was obtained and dried at 150 °C (Scheme 1).

2.3. Preparation of Epoxy Nanocomposites. Epoxy nanocomposites were prepared using solution mixing technique.\textsuperscript{34} The concentration of GO was fixed at 0.5 wt %. The required amount of GO and E-f-GO was dispersed in ethanol using bath sonication for 30 min. The epoxy resin was then added and sonicated for another 30 min. The mixture was kept under vacuum at 60 °C to evaporate the solvent. After solvent removal, it was mixed using a mechanical mixer with simultaneous sonication maintaining the bath temperature at 50 °C for 2 h at 400 rpm. The hardener was then added and mixed for 10 min at 500 rpm. Bubbles were removed by keeping the mixture in vacuum for 1 h. Then, the mixture was poured into a preheated Teflon-coated mold and cured at 60, 80, 100, and 120 °C for 30 min each cycle. This curing cycle was adopted to avoid void formation, which can be detrimental to composite properties.

2.4. Fabrication of CF Laminates. CF laminates were prepared using the VARTM technique, as shown in the Scheme 2. The CF mat was aligned at 0° and later the epoxy resin was infused in the CF mat. For laminate fabrication, CF-to-resin ratio was 50:50, which is commercially used for most of the applications. Laminates were cured in oven under same conditions.
conditions as epoxy nanocomposites and post cured at 140 °C. Table 1 gives the details of samples and sample denotations used in this work.

**Table 1. Sample Details**

| Sample                  | Sample Code |
|-------------------------|-------------|
| neat epoxy              | neat        |
| 0.5 wt % GO/epoxy       | GO/epoxy    |
| 0.5 wt % epoxy-f-GO/epoxy| E-f-GO/epoxy|
| epoxy/carbon fiber      | Ep/CF       |
| 0.5 wt % GO/epoxy/carbon fiber | GO/Ep/CF |
| 0.5 wt % E-f-GO/epoxy/carbon fiber | E-f-GO/Ep/CF |

**2.5. Characterization.** The effective grafting of the epoxy polymer on GO was confirmed using a PerkinElmer FTIR spectrometer. The percentage grafting of synthesized particles and thermal decomposition of the composites were monitored by a Netzsch STA 409 PC thermogravimetric analyzer at a rate of 10 °C/min in air. AFM was performed, and the variation in the thickness of GO sheets was observed using JPK Nanowizard AFM. TEM images were obtained using Tecnai G2 F30 at 300 kV. Raman spectra were obtained for different functionalized GO powder using a LabRAM HR (UV) system with 532 nm laser excitation. XRD patterns of GO and E-f-GO were collected using an XpertPro, PANalytical instrument in the range of 8°–40° 2Θ. The mechanical behavior was studied using a Q800 dynamic mechanical analyzer from TA Instruments. Thermal analysis was done using a Q2000 modulated differential scanning calorimeter. The samples were heated at a rate of 2 °C/min with a modulation of 1 °C from −30 to 160 °C. The microstructure of various samples was obtained using scanning electron microscopy (SEM). Lap shear test was carried out at 0.5 mm/min under tensile loading to measure the adhesion strength of epoxy nanocomposites. Electrical conductivity for epoxy nanocomposites was measured using a Novocontrol Alpha-N impedance analyzer in a broad frequency range of 12.4–160 GHz.

**3. RESULTS AND DISCUSSION**

**3.1. Synthesis and Characterization of E-f-GO.** FTIR spectra for functionalized GO (Figure 1a) confirm the successful synthesis of E-f-GO. For the synthesis of E-f-GO, the carboxylic and hydroxyl functional groups on the GO surface facilitate the epoxide ring-opening reaction. The emergence of new peaks at 1710, 1650, 1580, and 1495 cm⁻¹ confirms the presence of C=O stretching, C=O stretching, C=C bending, and C–C stretching (in the ring) and C–H bending, respectively. This further confirms the covalent functionalization of epoxy chains on GO sheets.

**Figure 1b** shows the XRD patterns for GO and E-f-GO. The peak at 9.5° indicates the diffraction peak for GO sheets. This characteristic peak of GO completely disappeared upon covalent functionalization with epoxy chains. The broadening and peak shift in E-f-GO and a new peak around 21° further suggest the partial reduction of GO and short-range restacking upon functionalization of GO.

From Raman spectra shown in Figure 1c, D- and G-band intensity ratio of GO was altered on functionalization with epoxy chains. For both samples, two sharp peaks were observed at 1356 (D-band) and 1603 cm⁻¹ (G-band). The I_D/I_G ratio for GO and E-f-GO was observed to be 1.23 and 1.46, respectively. Hence, degree of defects increased in GO sheets upon covalent functionalization. From intensity ratios of E-f-GO, it reflects that epoxy polymer chains created more disorder on GO sheets. It also confirms that epoxy chains have been attached to various reactive sites on GO and epoxy chains cross-linked two or more GO sheets.

The thermal decomposition behavior of GO, epoxy resin, and E-f-GO was studied (Figure 1d) to quantify the amount of the epoxy prepolymer on the GO sheets. The weight loss around 100 °C in GO is due to the evaporation of water. The labile oxygen functionalities like –COOH and –OH undergo pyrolysis at 200 °C and showed a 14% weight loss. The pyrolysis of carbon skeleton and more stable oxygen functionalities occurred at 450 °C. For E-f-GO, the initial dip corresponds to the removal of water molecules, and degradation of epoxy started 350 °C onward. There was no major degradation at 200 °C, which suggests a partial reduction of GO functional groups. The residual weight percentage of epoxy, E-f-GO, and GO are 9.28, 7, and 3.42%, respectively.

AFM micrographs obtained for GO and E-f-GO show variation in the sheet thickness (Figure 1e,f). Upon functionalization of GO, a thin layer of epoxy chains was observed and the morphology of GO has been altered. From the height image, it was observed that there is an increase in sheet thickness, which again confirms the presence of polymer chains on GO. The dispersion state of GO (vial A) and E-f-GO (vial B) in ethanol was monitored (Figure 1g). GO dispersion appeared brownish, whereas the E-f-GO solution appeared black, which also suggests the reduction of GO sheets.

**3.2. Analysis of Epoxy Nanocomposites.** **3.2.1. Microstructure of Various Epoxy/GO Nanocomposites.** Figure 2a–c shows the morphology of cryo-fractured epoxy nanocomposites. Figure 2a is the morphology of neat epoxy, which does not show any void formation. Hence, we can suggest that the processing conditions adopted for curing resulted in a defect-free surface. With the inclusion of different fillers, GO, and E-f-GO, the morphology of epoxy was altered (Figure 2b,c). GO sheets have various functional groups such as carboxyl, hydroxyl, and epoxide groups. Because of the presence of these functional groups, GO disperses well in the epoxy matrix. It is evident from SEM micrographs that the surface roughness was more in GO/epoxy compared to that in E-f-GO/epoxy. From this, we conclude that functionalization of the GO surface with the epoxy prepolymer enhanced in improving the dispersion state of GO. Because the weight fraction of GO is very low, that is, 0.5 wt %, we did not observe any prominent agglomeration. The well-dispersed E-g-GO alters the behavior of the epoxy matrix, which can further translate into enhanced macroscale properties.

**3.2.2. Dynamic Mechanical Response and Adhesion Behavior.** Dynamic mechanical analysis (DMA) was carried out to understand the effect of functionalization of GO on the mechanical response of epoxy nanocomposites. DMA is an effective and sensitive tool to study the interfacial region and can provide quantitative analysis of the contribution of functionalized GO to improve the mechanical behavior of composites. For DMA analysis, experiments were carried out using a three-point bending clamp in the temperature range of 30–160 °C at the rate of 5°/min, 10 Hz frequency, and 5 μm amplitude. Figure 3 shows storage modulus as a function of...
temperature for various epoxy nanocomposites. For neat epoxy, the storage modulus was lower than the filled system, whereas GO- and E-f-GO-filled epoxy nanocomposites showed higher storage moduli. It is known that storage modulus represents the material ability to store energy, in other words, the elastic response of the material under given deformation conditions. Hence, it is clear from the graph that E-f-GO improves the interface between epoxy and GO and provides resistance to the

Figure 1. (a) FTIR spectra of GO and E-f-GO; (b) XRD pattern for GO and E-f-GO; (c) Raman spectra for GO and E-f-GO; (d) TGA profiles for the epoxy prepolymer, GO, and E-f-GO; (e) AFM scan and the corresponding height profile of GO; (f) AFM scan and the corresponding height profile of E-f-GO; and (g) dispersion state of GO (vial 1) and E-f-GO (vial 2) in ethanol.
deformation caused during mechanical loading. The E-f-GO/epoxy nanocomposite showed an approx. 28% increment in storage modulus relative to neat epoxy.

The lap shear strength of epoxy nanocomposites was studied under tensile load using ASTM 1002. A CFRP was used as the base material. The lap shear strength results are shown in Table 2.

![Figure 2. SEM micrographs for epoxy nanocomposites (a) neat (10 000×); filled with (b) 0.5 wt % GO (20 000× magnification); and (c) 0.5 wt % E-f-GO (20 000× magnification).](image)

![Figure 3. Storage modulus as a function of temperature for various epoxy nanocomposites.](image)

![Figure 4. Adhesion response of various epoxy nanocomposites.](image)

![Figure 5. MDSC curves for epoxy nanocomposites.](image)

| Table 2. Lap Shear Strength of Epoxy Nanocomposites |
|-----------------------------------------------|
| sample           | lap shear strength (MPa) |
| neat             | 9                        |
| GO/epoxy         | 13                       |
| E-f-GO/epoxy     | 18                       |

| Table 3. Glass-Transition Temperatures of Epoxy Nanocomposites |
|-------------------|
| sample            | glass transition temperature $T_g$ (°C) |
| neat              | 129                                    |
| GO/epoxy          | 101                                    |
| E-f-GO/epoxy      | 132                                    |

deformation caused during mechanical loading. The E-f-GO/epoxy nanocomposite showed an approx. 28% increment in storage modulus relative to neat epoxy.

The lap shear strength of epoxy nanocomposites was studied under tensile load using ASTM 1002. A CFRP was used as the base material.
adherent. Figure 4 represents the load carried by the adhesive as a function of applied strain. Neat epoxy failed at the load of 3000 N, and the GO/epoxy nanocomposite could bear loads up to 4110 N. Unlike them, the E-f-GO/epoxy-based adhesive was able to withstand loads up to 5600 N. Hence, there was a 100% improvement in the lap shear strength of the E-f-GO/epoxy composite. It can be attributed to the strong interaction between the adhesive and adherent (Table 2). As discussed, SEM micrographs also showed well-dispersed modified GO in the host matrix. This also suggests that E-f-GO/epoxy can improve wettability with the CF surface.

3.2.3. Thermal Behavior and the Extent of Cross-linking. For thermoset polymers, such as epoxy, it is difficult to observe any transition using conventional differential scanning calorimetry (DSC) because of the cross-linked structure. Hence, for our analysis, we carried out an experiment using modulated DSC (MDSC), which gives information of both reversible and nonreversible $C_p$ values. The reversible $C_p$ tells about the glass-transition temperature of epoxy. Figure 5 shows reversible $C_p$ as a function of temperature for different epoxy systems, and $T_g$ is tabulated in Table 3. The experiment was carried out in the temperature range of 0–170 °C, ramp rate 5 °C/min, and 3000 N, and the GO/epoxy nanocomposite could bear loads up to 4110 N. Unlike them, the E-f-GO/epoxy-based adhesive was able to withstand loads up to 5600 N. Hence, there was a 100% improvement in the lap shear strength of the E-f-GO/epoxy composite. It can be attributed to the strong interaction between the adhesive and adherent (Table 2). As discussed, SEM micrographs also showed well-dispersed modified GO in the host matrix. This also suggests that E-f-GO/epoxy can improve wettability with the CF surface.

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### Table 4. Electrical Conductivity of CF Laminates

| sample               | conductivity (S/cm) |
|----------------------|---------------------|
| Ep/CF                | 14                  |
| GO/Ep/CF             | 1.3                 |
| E-f-GO/Ep/CF         | 0.6                 |
signals were modulated at ±1 °C for every 60 s under a nitrogen condition. From the result, it is clear that the presence of GO lowers the $T_g$ of the epoxy polymer, which is attributed to the reduction of effective cross-link volume, whereas the E-f-GO/epoxy nanocomposite showed a slight increase in the $T_g$ value. From this, we can conclude that epoxy functionalization of GO sheets can alter the molecular motion of epoxy chains and affect the extent of cross-linking to a minimum extent, thereby improving the state of dispersion of GO in host epoxy.

3.2.4. Charge Transport in Various Epoxy Nanocomposites. Figure 6 shows the electrical conductivity of epoxy nanocomposites as a function of frequency. Epoxy polymer is an electrical insulator, and because of the presence of $-\text{OH}$, $-\text{COOH}$, and $\text{C}=-\text{O}$ groups on the GO surface, it does not allow the movement of electric charge, unlike graphene which is a highly conductive material. Hence, GO/epoxy showed a completely insulating behavior. We know that reduced GO can enhance the electrical behavior of GO because of the less defective site. However, in our work, because GO reduction was carried out with epoxy chains, which is again insulating, the electrical behavior of E-f-GO/epoxy did not alter. This type of nanocomposites having a high adhesive strength and high electrical resistance can be used in electronic packaging industry.

3.3. Analysis of CF Laminates. From the above discussion, we can understand how E-f-GO affects various properties of the epoxy matrix. After thorough analysis of epoxy nanocomposites, we fabricated thin laminates with two layers of bidirectional woven CF mat and modified epoxy. Further, we studied mechanical and EMI shielding behavior of these laminates.

3.3.1. Morphology and the Interfacial Adhesion with the Host Matrix. Figure 7 shows the microstructure of different CF composites with epoxy (a), GO/epoxy (b), and E-f-GO/epoxy (c). From the SEM micrograph of Ep/CF, it is observed that there is nonuniform distribution of epoxy and improper adhesion with the fiber (see inset of Figure 7). This can lead to inferior properties of laminates and can cause severe damage during their service life. This issue can be dealt by improving the interface between the matrix and fiber. SEM micrographs of GO/Ep/CF also showed some delamination, however, to a lesser extent. In this case, few-layered stacks of GO driven by the strong van der Waal’s forces can impede their uniform dispersion in the host epoxy. Interestingly, E-f-GO/Ep/CF showed better adhesion of epoxy with the fiber surface. This can be attributed to the interaction between the surface functional group available on CF and modified GO sheets. It is envisaged that upon grafting epoxy chains onto GO, the sheets are well-exfoliated (as supported by XRD), resulting in their uniform dispersion. Moreover, in the case of E-f-GO, the presence of short epoxy chains ensures better interfacial adhesion with the host epoxy and the CF facilitated by E-g-GO “interconnects” (see inset of Figure 7). These observations can be well-correlated with the observed SEM images of the fractured laminates where lesser debonding can be seen from Figure 7c. These “interconnects” besides improving the structural properties (discussed in the next section) can also help in better charge transport at the interface (will be...
discussed in the following sections dealing with EMI shielding properties.

3.3.2. Dynamic Mechanical Response. The improvement in the matrix–fiber interface can be translated into an enhanced mechanical behavior. Figure 8 shows the storage modulus of different CF laminates as a function of temperature, and Figure 9 shows $\tan \delta$ as a function of temperature to evaluate the glass-transition temperature ($T_g$) of the laminates. DMA analysis becomes very critical in specific applications such as in aircrafts and missiles where the thermomechanical response determines the performance. All experiments were carried out in the linear viscoelastic region. For the Ep/CF composite, the storage modulus is approx. 17 GPa and $T_g$ is 117 °C, whereas GO/Ep/CF showed a slight improvement in the storage modulus. Further, we observed that E-f-GO/Ep/CF exhibited a high modulus value of 47 GPa, which suggests that there is a formation of strong interfacial bonding between the fiber and matrix. In other words, inclusion of E-g-GO in Ep/CF composites acted as “interconnects”, thereby improving the stress transfer at the interface. Hence, it can be concluded that E-f-GO/Ep/CF laminates can withstand mechanical deformation in a wide temperature range. From $\tan \delta$ plot as well, it is clear that molecular movement of the composite was restricted with the infusion of E-f-GO/epoxy into the CF mat. The broadness in $\tan \delta$ curve also indicates that there is a long-range relaxation in the composite.

3.3.3. Charge Transport and the Microwave Absorption Behavior. It is important to understand the electrical response of the composite, if we are considering EMI shielding application. Sheet resistance was measured using van der Paw method and later electrical conductivity of composites was calculated accordingly. Table 4 summarizes the calculated electrical conductivity of different CF laminates. It is evident that upon grafting GO with epoxy chains, the sheet resistance has increased as E-f-GO is localized as “interconnects” between host epoxy and CF. This observation is important from shielding EM radiation. If the skin is conducting, one may expect surface reflection, and if the skin offers more resistance, the incoming EM radiation can penetrate and interact with the entities in the shield.

Figure 10 represents $SE_{total}$ as a function of frequency for CF laminates. $SE_{total}$ was measured for different material under test (MUT) in the frequency range of 12–18 GHz using the waveguide setup (Scheme 3). It was observed that the electrical conductivity of Ep/CF composites did not alter significantly with the inclusion of GO and E-g-GO-filled epoxy. However, nanoparticles introduce heterogeneity in the CF composite, such a junction can also assist in enhancing SE. These junctions provide multiscale interfaces in conventional Ep/CF and might assist in improving the absorption of incident EM waves. In theory, for EMI shielding application, high electrical conductivity of material is not a necessary condition to attenuate
EM wave energy. In our study, we found that the E-f-GO/Ep/CF composite can shield the equipment up to 68 dB, which means >99% of the incident wave is being shielded. In contrast, Ep/CF and GO/Ep/CF composites showed SE of -22 and -50 dB, respectively (Figure 10). Metals are a homogeneous system having high electrical conductivity, causing shielding mainly through reflection and slightly through the absorption mechanism in which the energy of EM waves are exponentially reduced up to skin depth. Unlike metals, CF composites are not perfect conductors; hence, the reflection mechanism is not the only governing factor for shielding. CF laminates are dielectric lossy materials, which contribute to the absorption of EM waves. The formation of a heterogeneous junction between the nanofiller (GO and E-f-GO) and CF can deteriorate the wave energy, thus causing high SE. Further, % attenuation was calculated from $\frac{T + A + R}{T + A + R} = 1$, where $T$ is transmission, $R$ is reflectance, and $A$ is absorption (see Figure 10d). It was observed that E-f-GO/Ep/CF attenuated 99.999% of incident waves (>90% absorption) compared to 98% attenuation (70% absorption) showed by Ep/CF. This begins to suggest that thin sheets of E-f-GO/Ep/CF can replace conventional EMI shielding materials often used in the aircraft. This can further improve the aircraft efficiency without comprising its critical requirement of EMI shielding.

$$SE_{Total} = SE_R + SE_A + SE_M$$

$$SE_R = 10 \times \log_{10} \left( \frac{1}{1 - S_{11}} \right)$$

$$SE_A = 10 \times \log_{10} \left( \frac{1 - S_{11}^2}{S_{21}^2} \right)$$

From the results presented in Figure 10, it is clear that absorption is the main mechanism involved in the attenuation of incident electromagnetic radiation facilitated by the multiple reflection through epoxy-functionalized GO “interconnects”. $SE_R$ and $SE_A$ were measured using scattering parameters, $S_{21}$ and $S_{11}$ (eqs 2 and 3). $SE_R$ depends on the surface charge mobility of MUT, and from electrical conductivity results, we know that surface conductivity did not alter significantly with the inclusion of nanoparticles. Hence, $SE_R$ for all CF composites was below -10 dB, whereas $SE_A$ altered significantly in the presence of GO and E-f-GO, creating heterogeneity in the CF composites. For E-f-GO/Ep/CF composites, $SE_A > -50$ dB was observed in the frequency range of 12–18 GHz. It is envisaged that CF act as a wave guide and eventually absorbs the incident EM radiation through multiple scattering within the fabric. In our study, epoxy-functionalized GO is well-exfoliated in the host matrix, it acts as “interconnects”, thereby promoting multiple internal reflections through materials that show varied impedance (a cartoon illustrating this phenomenon is pictorially depicted in Scheme 4). This impedance mismatch results in the attenuation of the incoming EM radiation and manifests as absorption in the measured scattering parameters in a network analyzer. The increased sheet resistance further promotes the incoming EM radiation to penetrate into the shield and interact with the entities. As observed earlier that the sheet resistance is higher in the case of E-f-GO/Ep/CF laminates, higher absorption in this case can be expected. The rapid decay in the energy of EM waves is due to absorption phenomena eventually resulting in the conversion of the EM energy to thermal energy. This mechanism can cause an increase in the temperature of MUT (CF composites) when exposed to an EM environment. From literature it is well-known that CF and GO are excellent thermal conductors. We carried out an experiment to understand the thermal response shown by this microwave-absorbing material under exposure to EM waves. For this purpose, 1-port VNA was used and an EM wave was incident on samples using a waveguide (Scheme 5). CF composite samples were exposed to the EM radiation at a maximum frequency of 18 GHz and power level of 13 dBm for 10 min, and the thermal response was captured using a Fluke IR thermal imaging scanner. It was observed that there was no significant change in the temperature level for any of the laminates at a maximum frequency of 18 GHz (Figure 11). In addition, we assessed the thermal degradation of these laminates (not shown here). CF laminates degrade in two stages; first, epoxy three-dimensional network undergoes degradation at 350 °C, followed by CF degradation. Hence, it can be concluded that these materials can be used as an excellent microwave absorber with good thermal stability.

4. CONCLUSIONS

In the present work, we have attempted to understand the influence of an interface on the mechanical and EM absorption behavior of epoxy/CF composites. Covalent functionalization of GO sheets with epoxy chains was carried out, and a thorough characterization was done to confirm the chemical reduction of GO. Epoxy nanocomposites incorporated with 0.5 wt % of GO and E-f-GO were prepared using solution technique. Various thermal, mechanical, and electrical analyses were employed to study the influence of E-f-GO on the epoxy matrix. Further, laminates were fabricated with two layers of a woven CF mat and a modified epoxy nanocomposite was infused. On incorporating E-g-GO in epoxy/CF laminates, an impressive 175% improvement in the storage modulus, 100% enhancement in the lap shear strength, and an extraordinary 200% improvement in the SE at a very low filler content (0.5 wt %) were observed. Such a lightweight, thin yet strong EM
absorbing material can be a good alternative for the existing metal-based shields.

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**Notes**
The authors declare no competing financial interest.

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