Electronic Supplementary Material (ESI) for RSC Advances.

Supporting Information

Enhanced Microwave Absorption Properties of Conducting Polymers@Graphene Composite to Counteract Electromagnetic Radiation Pollution: Green EMI Shielding

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1. Experimental Details

1.1. Chemicals Used

Monomer 3,4-ethylene dioxythiophene (EDOT) (Kemiwork China), aniline was procured from Fisher Scientific, while graphite flakes were obtained from Himedia India. Potassium permanganate ($KMnO_4$), hydrochloric acid (HCl), sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), ammonium peroxydisulphate $(NH_4)_2S_2O_8$ (APS), dodecyl benzene sulfonic acid (DBSA) ($C_{12}H_{25}C_6H_4SO_3H$), isopropyl alcohol, and aqueous ammonia solution were procured from Merck India. All chemicals were of analytical grade and used without further purification.

1.2. Synthesis of composites

Initially, RGO (graphene) was chemically prepared from graphite flakes using the oxidative Hummer's method, as previously reported [1]. The polymer composites were then synthesized through an in-situ chemical oxidative polymerization method.

We successfully synthesized PEDOT/Pani and its composites with graphene through an in-situ chemical oxidative polymerization process using DBSA as both surfactant and dopant. The preparation involved homogenizing EDOT monomer and 0.3 M DBSA with a homogenizer for 2 hours at 25 °C, with continuous stirring for 12 hours. The polymerization reaction was initiated by adding APS drop by drop. After 12 hours, we obtained dark bluish precipitates of PEDOT sample, which were demulsified with propanol, filtered, washed with distilled water, and finally dried at 65 °C to obtain the sample. This chemical oxidative emulsion polymerization reaction, conducted at lower temperature, resulted in long and homogeneous PEDOT chains with high molecular weight, enhancing the overall conductivity. To further explore the impact of graphene and

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copolymerization with Aniline on the shielding properties of PEDOT composites, we synthesized various composite samples with different weight/mol ratios of as mentioned in Table S1.

Table S1. *Details of sample names with their composition.*

Sample code	DBSA (M)	APS (M)	*RGO (graphene)*	*EDOT (M)*	*Aniline (M)*
PEDOT	0.3	0.1	--	0.1	--
Pani	0.3	0.1	--	--	0.1
PG	0.3	0.1	2.6 gm	0.1	--
PaniG	0.3	0.1	2.6 gm	--	0.1
PPG	0.3	0.1	2.6 gm	0.05	0.05

1.3. Characterizations Techniques

The investigation of the conducting polymer composites samples involved a comprehensive characterization using various analytical techniques.

XRD (X-ray Diffraction) Analysis: Rigaku Mini Flex 600 XRD instrument was employed to perform X-ray diffraction analysis, which provided insights into the structural properties of the samples.

SEM (Scanning Electron Microscopy): SEM (Carl Zeiss AG Supra 55VP) with an accelerating voltage of 5-30 kV was used to conduct scanning electron microscopy, allowing for the observation and analysis of the morphological features of the materials.

FTIR (Fourier Transform Infrared Spectroscopy) Analysis: The Thermo iS50 FTIR instrument was used in conjunction with KBr pallets to investigate the characteristic functional groups present within the materials.

Electromagnetic Shielding and Dielectric Measurements: Electromagnetic shielding and dielectric properties were measured within the Ku frequency band (12.4 to 18 GHz) using a PNA (Performance Network Analyzer) from Agilent, model N5230C. To facilitate these measurements, powder samples were compacted into rectangular shapes matching the dimensions of the sample holder (15.8 × 7.9 mm^2). Subsequently, these samples were inserted into the sample holder, connecting them to the waveguide flanges of the network analyzer.

2. Electromagnetic Shielding Calculation

The shielding effectiveness of the samples has been assessed through measuring scattering parameters S_{11}, S_{22}, S_{12}, and S_{21}. S_{11} and S_{22} correspond to the reflection (R) coefficient of electromagnetic waves, while S_{12} and S_{21} pertain to their transmission (T) coefficient through the test material. The reflection of electromagnetic waves by the shielding material can be computed as;

$$R = |S_{11}|^2 = |S_{22}|^2 \tag{S1}$$

The transmission of electromagnetic wave can be computed through the utilization of transmission scattering parameters as;

$$T = |S_{12}|^2 = |S_{21}|^2 \tag{S2}$$

And the reflection (R) coefficient and absorbance (A) coefficient can be calculated as;

$$A = 1 - R - T \tag{S3}$$

$$A_{eff} = (1 - R - T)/(1 - R) \tag{S4}$$

where A_{eff} is the effective absorbance. From these R & T coefficients/ scattering parameters, the shielding effectiveness due to absorption (SE_A) and reflection (SE_R) can be calculated as;

$$SE_A(dB) = -10\log\left[1 - A_{eff}\right] = -10\log\left[T/(1 - R)\right] \tag{S5}$$

$$SE_R(dB) = -10\log(1 - R) \tag{S6}$$

The shielding effectiveness due to absorption (SE_A) and reflection (SE_R) are also function of material thickness (t) and the skin depth (δ), which can be described as;

$$SE_A(dB) = 20\frac{t}{\delta}\log e = 20t\sqrt{\frac{\mu_r\omega\sigma_s}{2}}\log e \tag{S7}$$

$$SE_R(dB) = 10\log\left(\frac{\sigma_s}{16\omega\mu_r\varepsilon_o}\right) \tag{S8}$$

where;

$$\sigma_S = \omega\varepsilon_o\varepsilon'' \tag{S9}$$

$$\delta = \sqrt{2/\mu_r\omega\sigma_s} \tag{S10}$$

where μ, σ_s and f are the permeability, conductivity and frequency, respectively.

Table S2: Reflection loss (R_L) and EMI shielding effectiveness of various composites.

Composites (filler/matrix)	Thickness (mm)	SE_T/ R_L (dB)	Frequency (GHz)	Manuscript Ref. no.	Ref. no.
PEDOT/graphene nanoplatelet	2	17.6	12	[62]	[2]
Pani/graphene nanoplatelet	1.5	14.5	12	[44]	[3]
Pani/Red Mud	3	41	12.4	[63]	[4]
Polypyrrole/graphene	2	33	8.2	[64]	[5]
Polypyrrole/$CoFe_2O_4$/graphene	2	38	8.2	[65]	[6]
Pani/suede-like cloth (SLC)	2.6	26	8.2	[66]	[7]
PEDOT:PSS/polyvinyl butyral (PVB)	3.9	47.5	12.4	[67]	[8]
PEDOT/Fe_3O_4	--	43.4	14	[68]	[9]
PEDOT/wood	2	46.2	12.4	[69]	[10]
MoS_2/PEDOT/rGO	2.1	32.41	17.84	[70]	[11]
CNTs/MXene/CS	8	29.3	12.4	[71]	[12]
PEDOT/graphene (PG) PEDOT/Pani/graphene (PPG)	2	46.53 42.96	18 GHz	Present work	Present work

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