Transparent multi-layer graphene/polyethylene terephthalate structures with excellent microwave absorption and electromagnetic interference shielding performance

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Supplementary Information

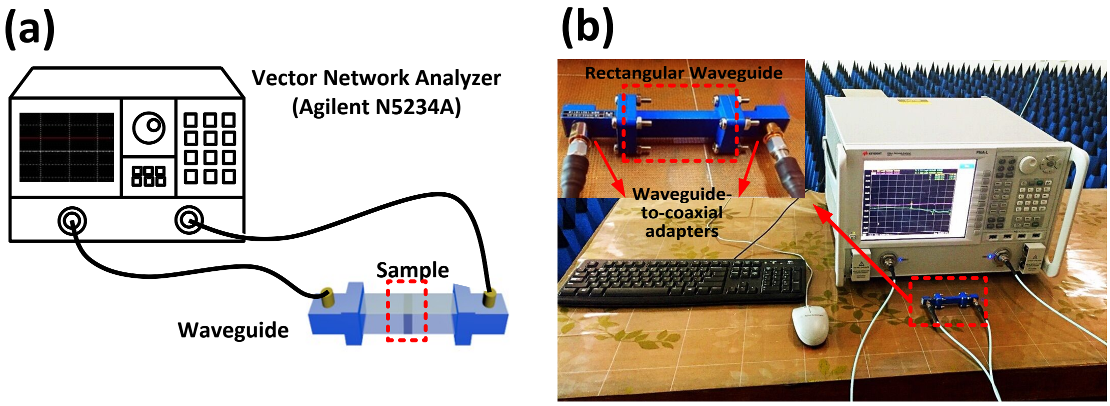

Figure S1 (a) Schematic drawing and (b) photo of the measurement setup for the electromagnetic shielding performance of samples.

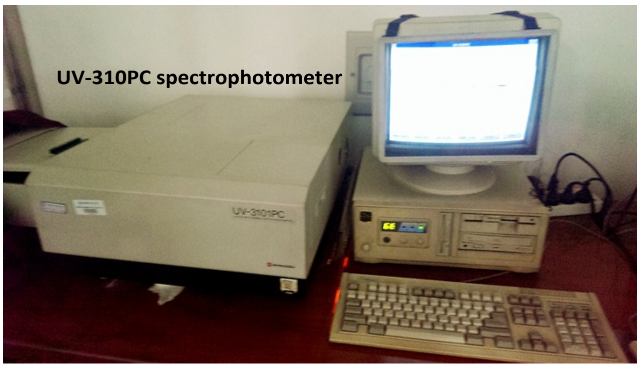

Figure S2 Photo of the measurement setup for the visible transmittance of samples.

Theory

Matching the solution of the Maxwell equations with the boundary conditions at $z = nd$, we obtained the following equations

$$E_i^0 + E_r^0 = E_i^1 + E_r^1$$

$$K_s(E_i^1 - E_r^1) = K_a(E_i^0 - E_r^0)$$

$$E_i^1 \exp(iK_s l) + E_r^1 \exp(-iK_s l) = E_i^2 + E_r^2$$

$$K_S E_i^2 - K_s[E_i^1 \exp(iK_s l) - E_r^1 \exp(-iK_s l)] = -K_a B(E_i^2 + E_r^2)$$

$$E_i^2 \exp(iK_s l) + E_r^2 \exp(-iK_s l) = E_i^3 + E_r^3$$

$$K_S E_i^3 - K_s[E_i^2 \exp(iK_s l) - E_r^2 \exp(-iK_s l)] = -K_a B(E_i^3 + E_r^3)$$

□

$$E_i^N \exp(iK_s l) + E_r^N \exp(-iK_s l) = E_t^N$$

$$K_a E_t^N - K_s[E_i^N \exp(iK_s l) - E_r^N \exp(-iK_s l)] = -K_a B E_t^N$$

where K_S and K_a denote the wavenumber of the substrate (PET films here) and air, respectively.

Based on matrix theory, we got the following equations

$$\begin{bmatrix} E_i^N \\ E_r^N \end{bmatrix} = \begin{bmatrix} \dfrac{(K_s + K_a + K_a B)}{2K_s \exp(iK_s l)} \\ \dfrac{(K_s - K_a - K_a B)}{2K_s \exp(-iK_s l)} \end{bmatrix} E_t^N$$

$$\begin{bmatrix} E_i^{N-1} \\ E_r^{N-1} \end{bmatrix} = \begin{bmatrix} \dfrac{(2K_s + K_a B)}{2K_s \exp(iK_s l)} & \dfrac{(K_s + K_a B)}{2K_s \exp(iK_s l)} \\ \dfrac{(-K_a B)}{2K_s \exp(-iK_s l)} & \dfrac{(K_s - K_a B)}{2K_s \exp(-iK_s l)} \end{bmatrix} \begin{bmatrix} E_i^N \\ E_r^N \end{bmatrix}$$

□

$$\begin{bmatrix} E_i^0 \\ E_r^0 \end{bmatrix} = \begin{bmatrix} \dfrac{(K_s + K_a)}{2K_a} & \dfrac{(K_a - K_s)}{2K_a} \\ \dfrac{(K_a - K_s)}{2K_a} & \dfrac{(K_a + K_s)}{2K_a} \end{bmatrix} \begin{bmatrix} E_i^1 \\ E_r^1 \end{bmatrix}$$

By solving the above equations, we derived that

$$\begin{bmatrix} E_i^0 \\ E_r^0 \end{bmatrix} = ABCE_t^N$$

where

$$A = \begin{bmatrix} \dfrac{(K_s + K_a)}{2K_a} & \dfrac{(K_a - K_s)}{2K_a} \\ \dfrac{(K_a - K_s)}{2K_a} & \dfrac{(K_a + K_s)}{2K_a} \end{bmatrix}, B = \begin{bmatrix} \dfrac{(2K_s + K_a B)}{2K_s \exp(iK_s l)} & \dfrac{(K_s + K_a B)}{2K_s \exp(iK_s l)} \\ \dfrac{(-K_a B)}{2K_s \exp(-iK_s l)} & \dfrac{(K_s - K_a B)}{2K_s \exp(-iK_s l)} \end{bmatrix}^{\wedge(N-1)}, C = \begin{bmatrix} \dfrac{(K_s + K_a + K_a B)}{2K_s \exp(iK_s l)} \\ \dfrac{(K_s - K_a - K_a B)}{2K_s \exp(-iK_s l)} \end{bmatrix}$$

During the graphene preparation, we didn't wash off the PMMA on it to avoid additional damage to the surface of graphene sheets and to protect graphene in the course of the experiment. Because the electromagnetic properties of PMMA is quite similar to PET, and the thickness of PMMA (5 μm) is far less than the PET films (1 mm). The effect of the PMMA is negligible. The dielectric constant of the PET substrate used in the calculations was 3. The chemical potential μ_c and the scattering rate Γ of graphene used in the calculations was 0.3 eV and 3.80 meV, respectively.