Carbon films as perfect electromagnetic wave absorbers and anti-reflectors

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It is shown that thin carbon coating with thicknesses, depending on its structure and porosity, ranging from tens of nanometres to tens of microns can absorb almost all incident microwave radiation without reflection. Special conditions on dielectric properties of substrate and conductivity of carbon material, which are necessary for the realisation of such a perfect absorber, are derived. The conductance of the carbon coating can then be controlled by proper porosity.

1. Introduction: Usually, it is considered that conductive films with thicknesses much less than their skin depths ($d \ll l_{\text{skin}} \sim 1/\sqrt{\sigma\omega}$, l_{skin}, ω are skin depth and frequency) are transparent for electromagnetic radiation. However, the nanometrically thin metals and metal-like films having skin depth $\sim 1-10\,\mu\text{m}$ demonstrate strong absorption and reflection of incident electromagnetic waves, up to 75% in total caused by 50% absorption and 25% reflection [1–3]. The most extreme case of a thin film is graphene, with thickness of single atomic diameter. The description of such a material is not possible by the means of the three-dimensional (3D) conductivity σ. Instead, graphene's electromagnetic transmission properties must be described by the 2D sheet conductance σ_{sheet} [4–6].

The following expressions govern the interaction of the incident wave with a single suspended graphene flake:

$$T = \frac{1}{(1+l')^2}, \quad R = \frac{l'^2}{(1+l')^2}, \quad A = \frac{2l'}{(1+l')^2}, \qquad (1)$$

where $l' = \sigma_{\text{sheet}}/(2\varepsilon_0 c)$ is a dimensionless factor, T, R, and A are transmittance, reflectance, and absorptance of the incident wave in the sheet, respectively. Transmittance decreases whereas reflectance increases with the corresponding increase in the sheet conductance σ_{sheet}. Absorptance reaches its maximum of 50% at $l' = 1$ according to (1). Conductive films with the thickness exceeding the electron's free path can be described by macroscopic electrodynamics with specific conductance σ. However, for the thicknesses much less than the skin depth the film's transmission/reflection properties can be approximately described with the help of effective sheet conductance $\sigma_{\text{sheet}} = \sigma d$, where d is the film thickness. This is the direct consequence of the Ohm's law, which states that conductance of the lump element is proportional to its cross section. Expression (1) with the above mentioned substitution holds true in this case. To achieve the desired absorption characteristics one has to control the necessary film properties, such as conductivity and thickness. For example, $\sigma d/(2\varepsilon_0 c) = 1$ is the condition for the absorption maximum of the suspended film. One usually chooses to vary the film thickness d to achieve the optimal highest absorption. Sometimes the thickness is fixed or limited by the technological process. In this case, one might choose the material, with the required conductivity, to satisfy the necessary optimal conditions for absorption/reflection. Present communication discusses the possibility to use micro or nanoporosity to tune the overall conductivity of the carbon film to achieve high shielding ability along with anti-reflection properties.

This Letter is structured as follows: The main physical ideas are presented in Section 2. These ideas are based on the 2D conductive layer approximation (with the sheet conductance σ_{sheet}). The numerical results accounting for the finite thickness of the carbon films are presented in Section 3. Section 4 gives the concluding remarks.

2. High absorption, small reflection: main ideas: Standard boundary conditions in electromagnetic problems usually consist of continuity of tangential electric and magnetic field components. As mentioned above, if the thickness of a conducting film is much less than the skin depth then its interaction with the electromagnetic wave can be described by effective sheet conductance. The boundary conditions for the tangential magnetic component of such a conductive sheet in this limited case can be approximately written in terms of continuity of the tangential to the sheet component of the electric field and discontinuity of the magnetic field:

$$\begin{aligned} &\boldsymbol{E}_{\text{t}}(z_i+0) = \boldsymbol{E}_{\text{t}}(z_i-0) \\ &\boldsymbol{H}_{\text{t}}(z_i+0) - \boldsymbol{H}_{\text{t}}(z_i-0) = [\boldsymbol{j}_{\text{surf}}(z_i) \times \boldsymbol{n}.] \end{aligned} \qquad (2)$$

Here $\boldsymbol{j}_{\text{surf}} = \sigma_{\text{sheet}}\boldsymbol{E}_{\text{t}}$ is the surface current induced by the electromagnetic field, $\boldsymbol{E}_{\text{t}}$ is the electric field component tangential to the surface, and z_i is the coordinate of the interface. This expression implies that the tangential component of the magnetic field has a discontinuity which is proportional to the surface current induced by the wave. The same boundary conditions are also true in the case of a graphene sheet when usual specific conductivity has no sense. Let us consider the transmission of the electromagnetic wave through a thin conductive film placed on top of a dielectric substrate with dielectric constant ε, and examine the possibility of large wave absorption and no reflection. Having satisfied the boundary conditions, in the case of a quarter-wave substrate (when radio frequency current, and therefore the ohmic absorption within the thin film are maximised), will lead to the following expressions for reflection, transmission, and absorption coefficients:

$$R = \left(\frac{1-\varepsilon+(\sigma_{\text{sheet}}/2\varepsilon_0 c)}{1+\varepsilon+(\sigma_{\text{sheet}}/2\varepsilon_0 c)}\right)^2, \quad T = \frac{4\varepsilon}{\left(1+\varepsilon+(\sigma_{\text{sheet}}/2\varepsilon_0 c)\right)^2},$$
$$A = \frac{4\varepsilon(\sigma_{\text{sheet}}/2\varepsilon_0 c)}{\left(1+\varepsilon+(\sigma_{\text{sheet}}/2\varepsilon_0 c)\right)^2}. \qquad (3)$$

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Using (3) one can see that reflectance can be suppressed at

$$\varepsilon = 1 + \frac{\sigma_{\text{sheet}}}{2\varepsilon_0 c}. \tag{4}$$

Absorptance is maximal at this point and it is described by the expression:

$$A = \frac{(\sigma_{\text{sheet}}/2\varepsilon_0 c)}{1 + (\sigma_{\text{sheet}}/2\varepsilon_0 c)}. \tag{5}$$

Almost total absorption can be reached if $(\sigma_{\text{sheet}}/2\varepsilon_0 c) \gg 1$. In the above estimations, we have considered the conductive film as a 2D sheet with sheet conductance σ_{sheet}. Expressions (1)–(5) are written for the normal wave incidence. From boundary problem solution, it is easy to see that in the inclined incidence geometry the following substitutions should be made in these formula: (i) for *s*-polarised wave $\sigma \to \sigma/\cos\theta$, $\sigma_{\text{sheet}} \to \sigma_{\text{sheet}}/\cos\theta$, $\varepsilon \to (\varepsilon - \sin^2\theta)/\cos^2\theta$; and (ii) for *p*-polarised wave $\sigma \to \sigma\cos\theta$, $\sigma_{\text{sheet}} \to \sigma_{\text{sheet}}\cos\theta$, $\varepsilon \to \varepsilon^2\cos^2\theta/(\varepsilon - \sin^2\theta)$. Hence the 'effective' value of conductivity increases for *s* polarisation and decreases for *p* polarisation in inclined geometry.

An exact account of the film thickness is provided in Section 3.

3. Numerical results: Boundary conditions for a conducting film deposited on a dielectric substrate have the form:

$$\begin{aligned}
b_0^+ + b_0^- &= b_1^+ + b_1^-,\\
b_0^+ - b_0^- &= \sqrt{\varepsilon}\left(b_1^+ - b_1^-\right),\\
b_1^+ \exp\left(ik\sqrt{\varepsilon}l_1\right) + b_1^- \exp\left(-ik\sqrt{\varepsilon}l_1\right) &= b_2^+ + b_2^-,\\
\sqrt{\varepsilon}\left[b_1^+ \exp\left(ik\sqrt{\varepsilon}l_1\right) - b_1^- \exp\left(-ik\sqrt{\varepsilon}l_1\right)\right] &= \sqrt{\varepsilon_m}\left(b_2^+ - b_2^-\right),\\
b_2^+ \exp\left(ik\sqrt{\varepsilon_m}l_2\right) + b_2^- \exp\left(-ik\sqrt{\varepsilon_m}l_2\right) &= b_3^+,\\
\sqrt{\varepsilon_m}\left[b_2^+ \exp\left(ik\sqrt{\varepsilon_m}l_2\right) - b_2^- \exp\left(-ik\sqrt{\varepsilon_m}l_2\right)\right] &= b_3^+.
\end{aligned} \tag{6}$$

Here the continuity conditions for the tangential components of the electric and magnetic fields on all the boundaries are given, with l_1, ε, l_2, and ε_m being thicknesses and dielectric constants of the dielectric plate and the conductive film, respectively, $b_i^\pm$ are coefficients of 'forward' and 'backward' waves. Index i represents set of different mediums: 0, 3 for air, 1 for dielectric plate and 2 for conductive film, $k = \omega/c$. Transmittance and reflectance are expressed through coefficients (6) as

$$T = \left|\frac{b_3^+}{b_0^+}\right|^2, \quad R = \left|\frac{b_0^-}{b_0^+}\right|^2. \tag{7}$$

Absorptance is derived from (7) as $A = 1 - T - R$. Figs. 1 and 2 demonstrate the dependence of absorptance and reflectance on the thickness of conductive plate for $\varepsilon = 3.5$ (quartz for example) and $\varepsilon = 10$ (aluminium oxide for example). The calculation is given for 30 GHz (*Ka* band). The quarter wavelength thicknesses of the dielectric are chosen in both cases: (1.3 mm in the first case and 0.8 mm in the second case). It can be seen, that absorptance has reached its maximum while reflectance is suppressed if the film properties almost correspond to (4). This condition requires definite values for the dielectric constant and conductance. There are well-developed techniques of producing dielectric materials with the values of the dielectric constant ε ranging from several tens to thousands [7, 8].

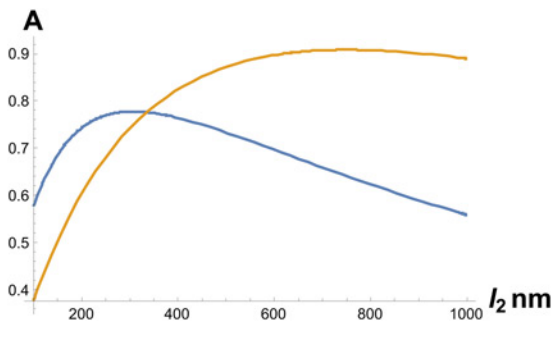

Fig. 1 *Dependence of absorptance on conducting film thickness for $\varepsilon = 3.5$ (blue curve) and $\varepsilon = 10$ (brown curve). Dielectric plate thickness correspond to quarter wavelength*

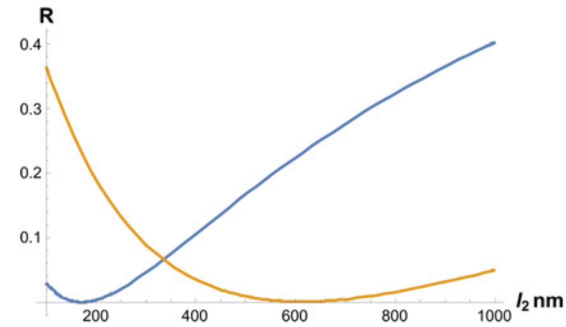

Fig. 2 *Dependence of reflectance on conducting film thickness for $\varepsilon = 3.5$ (blue curve) and $\varepsilon = 10$ (brown curve). Dielectric plate thickness correspond to quarter wavelength*

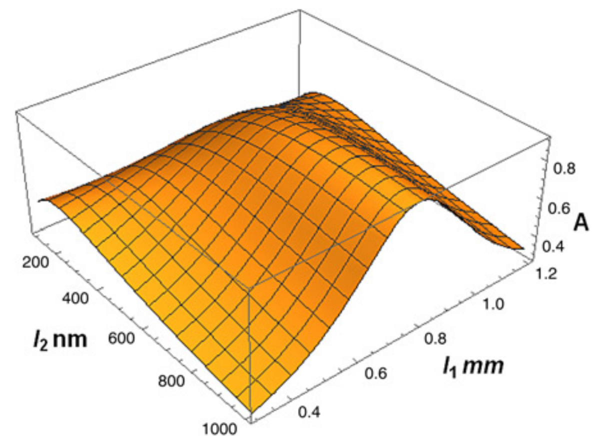

Fig. 3 *Absorptance dependence on the dielectric (l_1) and conductive film (l_2) thicknesses*

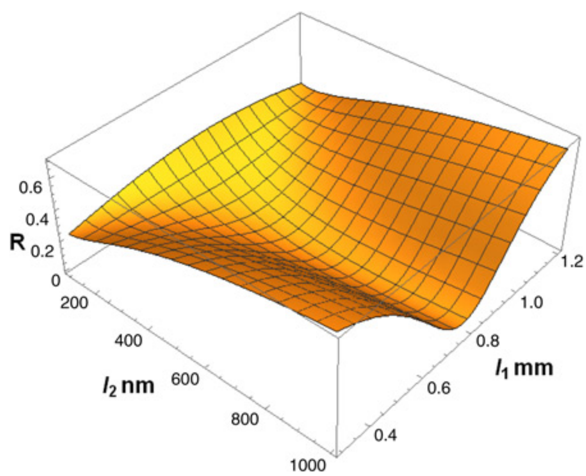

Fig. 4 *Reflectance dependence on the dielectric (l_1) and conductive film (l_2) thicknesses*

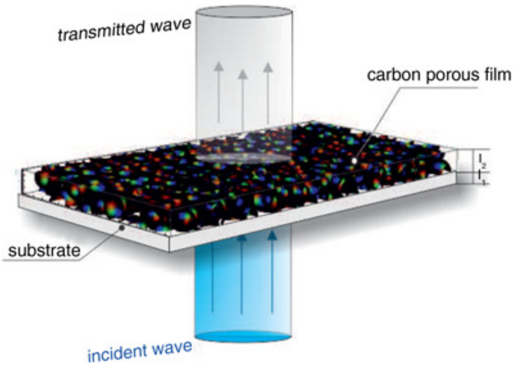

Fig. 5 *Geometry of wave incidence on structure 'dielectric substrate + porous conductive film'*

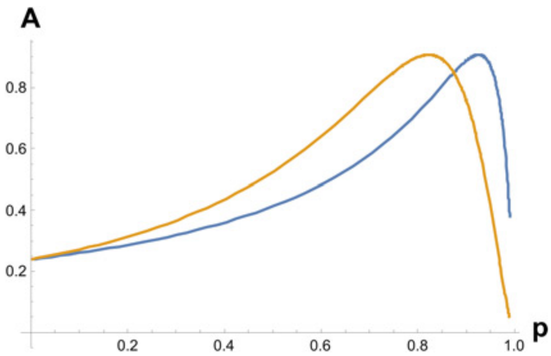

Fig. 6 *Absorptance dependence on conductor porosity (p). Dielectric constant of substrate $\varepsilon = 10$, film thickness $l_2 = 10\,\mu m$. Brown curve corresponds to asymmetrical Bruggeman model, blue curve corresponds to linear proportionality of conductance and film density*

The required value for specific conductance can be achieved by varying the porosity of the material.

Maximum absorptance exceeds 90% at approximately zero reflectance for $\varepsilon = 10$. 3D plots of both absorptance and reflectance are demonstrated in Figs. 3 and 4. Maximum absorptance and suppressed reflectance are at the point of quarter-wavelength and 'dielectric constant–conductance' matching (4).

Absorptance, reflectance, and transmittance depend on the value of the sheet conductance (σ_{sheet}). It can be varied by changing either the thickness or conductivity of the material. For conduction in porous materials, the medium's conductivity can be varied by choosing its porosity (see Fig. 5). Porous material can be considered as one of the composite materials composed of fractions possessing different dielectric constants. There is a whole variety of theoretical and phenomenological models of effective dielectric constants of such materials [9]. Applicability of every such model, however, must be checked experimentally in every case. In Figs. 6 and 7, the calculated dependence of absorptance and reflectance on porosity p for two models is shown. Blue curve corresponds proportionally to material density ($\sim 1 - p$) conductivity. The brown curve corresponds to asymmetrical Bruggeman model [10–12] with $(1 - p)^{3/2}$ dependence.

Maximum absorptance in the 10 μm film is reached at ~92 and ~80% porosities in the framework of these models.

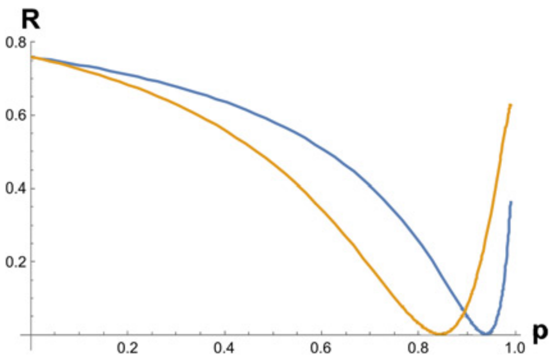

Fig. 7 *Reflectance dependence on conductor porosity (p). Dielectric constant of substrate $\varepsilon = 10$, film thickness $l_2 = 10\,\mu m$. Brown curve corresponds to asymmetrical Bruggeman model, blue curve corresponds to linear proportionality of conductance and film density*

4. Conclusions: We have demonstrated that using porous carbon films, maximum absorptance, and suppressed reflection can be reached simultaneously. Such property of porous carbon thin films (such as pyrolytic carbon films with high porosity [13]) can be applied when the reflection from other elements of the construction or circuit is undesirable. It was shown that when a carbon film is placed on top of a dielectric substrate with $\varepsilon = 10$ and the carbon film conductance matches the value of the dielectric constant, the absorptance reaches more than 90%. At higher dielectric constants (tens and more) [7, 8] almost perfect absorption can be reached. This brings us closer to the design of materials perfectly absorbing EM radiation, which in turn is crucially important for the development of compact effective shielding layers for practical applications, including shielding of nanooptoelectronic devices, screening of 5G communication systems, and other problems related to EMC.

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6 References

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