Optically transparent microwave screens based on engineered graphene layers

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Abstract: We propose an innovative approach for the realization of a microwave absorber fully transparent in the optical regime. This device is based on the Salisbury screen configuration, which consists of a lossless spacer, sandwiched between two graphene sheets whose sheet resistances are different and properly engineered. Experimental results show that it is possible to achieve near-perfect electromagnetic absorption in the microwave X-band. These findings are fully supported by an analytical approach based on an equivalent circuital model. Engineering and integration of graphene sheets could facilitate the realization of innovative microwave absorbers with additional electromagnetic and optical functionalities that could circumvent some of the major limitations of opaque microwave absorbers.

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1. Introduction

Microwave absorbers (or Radar Absorbing Materials, RAMs) have been realized in different fashions such as pyramidal absorbers, films, foams, metamaterials, to name a few [1–3]. Generally speaking, these devices are not optically transparent in the visible range. On the other hand, optically transparent absorbers could be used for military camouflage and shielding systems as well as successfully integrated in window glass and along with photovoltaics. This is also extremely important for micro and nano satellite applications where the maximization of the surface area for the solar power collection remains a critical issue.

In this context, the literature contains few efforts where researchers tried to overcome this limitation by realizing optically-transparent microwave absorbers. For example, one attempt is reported in [4] where the high imaginary part of the complex permittivity is used. In this particular case, the poly-ionic material exhibits high losses in the microwave range (poorly transparent) while showing a transmittance of about 90% in the visible range [4]. The main limitation of this solution is related to the fact that the optical properties cannot be tuned or engineered because they are only related to the material composition.

A few others recent works [5–8] have demonstrated the potential of graphene as optical transparent material for the realization of microwave absorbers. In this range, graphene sheet conductivity σ can be approximated by the DC sheet conductivity σ_{DC}, hence, microwave absorption can be modulated by properly engineering graphene sheet resistance R_s [9,10]. In [5,6], Wu et al and Balci et al proposed graphene absorbers based on a Salisbury screen configuration. A Salisbury screen consists of a lossless spacer sandwiched between a reflecting surface (mirror) and a thin absorbing layer [11]. The thickness of the lossless spacer is set equal to $\lambda/4$ in order to achieve destructive interference leading to perfect absorption at the resonant wavelength λ. It is worth highlighting that these graphene-based devices lack optical transparency as they mostly use metallic mirrors as reflectors which make them optically opaque. To overcome this constraint, the back-side metallic mirror can be replaced by metallic meshes, as reported in [7,8]. However, this alternative approach is not only technologically complicated due to various lithography steps involved in fabrication but also the achieved transparency is not high (only 62%).

In this work, we present a microwave screen based on a Salisbury configuration with properly engineered graphene sheets acting as both absorbing and reflecting layers and, thus, providing optical transparency as well as a simple and easy to fabricate device configuration.

We exploit a chemical route previously reported in [10] for tuning the electromagnetic response of graphene in the microwave range from the lossy-dielectric to the quasi-metallic regime. Specifically, we perform the chemical doping of multilayer graphene by $SOCl_2$ treatment for drastically reducing its sheet resistance R_s (below 30 Ω/sq). This protocol allows us to fabricate graphene providing a microwave reflectance larger than 80% that can be used as reflecting layer in a Salisbury screen in substitution of metallic mirrors or meshes.

Since the Salisbury screen absorption derives from the interplay between interference and losses between both absorbing and reflecting layers, the microwave response and, thus, R_s of the graphene foil acting as absorbing layer must be also finely tuned in order to achieve the highest absorbance [12]. For this reason, we have exploited the plasma-chemistry for the processing of graphene absorbing layer with hydrogen atoms and the fine-tuning of its sheet resistance R_s. The covalent attachment of hydrogen atoms to graphene breaks the π-conjugation with detrimental effects on its transport properties. We use a mild modulated

plasma source of hydrogen atoms in order to provide the full control of the kinetics of graphene hydrogenation [13]. In this way, we can finely increase the R_s of a multilayer graphene up to the specific value that is expected to provide the best performance as absorbing layer in a Salisbury screen configuration.

2. Analytical and numerical results

Figure 1(a) depicts the optically-transparent graphene-based microwave absorber that implements the Salisbury screen configuration. A transparent, lossless, dielectric spacer is sandwiched between two graphene sheets that have sheet resistances equal to R_{sa} (absorbing layer) and R_{sm} (mirror), respectively.

Figure 1(b) depicts the experimental setup where the proposed absorber is realized by stacking N glass slabs with a fixed thickness equal to 1.2 mm [see inset in Fig. 1(b)]. The graphene-based microwave absorber caps a WR90 rectangular waveguide (cross section: $a = 22.86$ mm and $b = 10.16$ mm). We set the operating frequency equal to 9 GHz, allowing the air-loaded waveguide to support only the fundamental mode TE_{10}.

The transmission-line model illustrated in Fig. 1(c) approximates very well the experimental configuration. In particular, the lossless spacer can be considered as a dielectric-loaded rectangular waveguide (having characteristic impedance and length equal to $Z_{TE10,\varepsilon}$ and d, respectively) that is interposed between two air-filled rectangular waveguide sections (having characteristic impedance equal to Z_{TE10}).
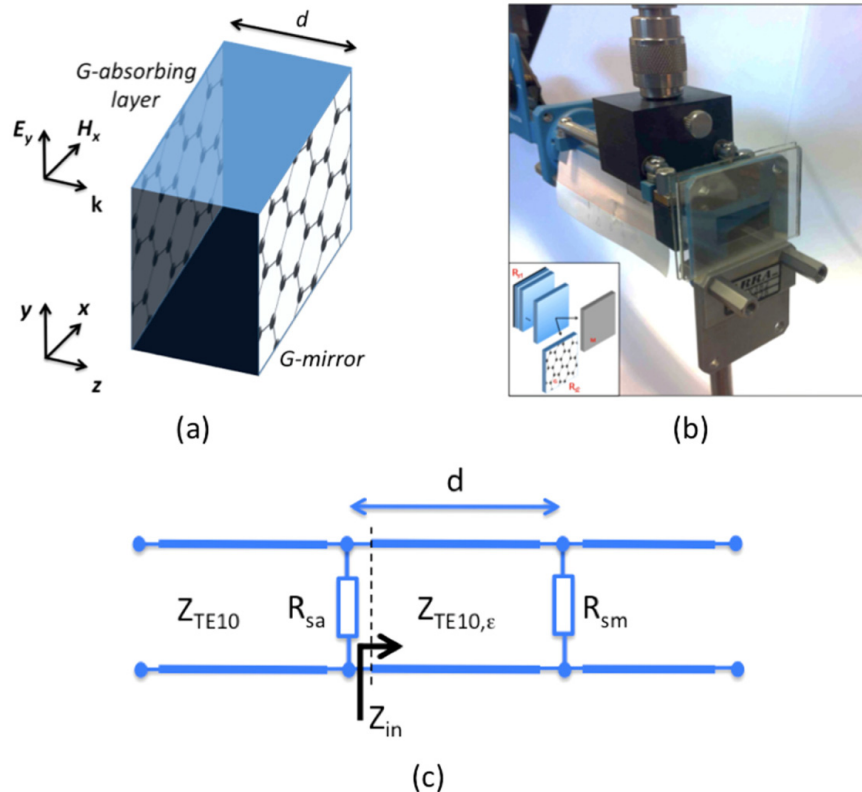

Fig. 1. (a) Sketch of the graphene-based Salisbury screen: the graphene-absorbing layer and the graphene-based mirror are separated by a transparent spacer with thickness d. (b) Picture of the graphene-based absorber: this device is fully transparent since the inner sidewalls of the rectangular waveguide are clearly visible; (inset) stacked glass slabs with identical thicknesses (1.2 mm) that constitute the lossless spacer. (c) Equivalent circuital model.

These waveguides are modeled as transmission lines while the graphene sheets are taken into account by means of two lumped admittances (R_{sa} and R_{sm}). Reflectance (R), transmittance (T) and absorption (A) were evaluated by means of the transfer matrix method. In particular, the transmission matrix of the whole system can be related to the matrixes of the single sections:

$$M = M_{Rsa} M_{spacer} M_{Rsm} = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{R_{sa}} & 1 \end{bmatrix} \begin{bmatrix} \cos(\beta d) & jZ_{TE10,\varepsilon}\sin(\beta d) \\ \dfrac{j}{Z_{TE10,\varepsilon}}\sin(\beta d) & \cos(\beta d) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1}{R_{sm}} & 1 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

(1)

where M_{Rsa}, M_{spacer} and M_{Rsm} correspond to the absorbing layer, spacer, and mirror matrices; β is the propagation constant of the transmission line.

Reflectance, transmittance and absorption can be calculated by means of the scattering parameters as follows:

$$R = |S_{11}|^2 = \frac{M_{11} + M_{12}/Z_{TE10} - M_{21}Z_{TE10} - M_{22}}{M_{11} + M_{12}/Z_{TE10} + M_{21}Z_{TE10} + M_{22}}$$

(2)

$$T = |S_{21}|^2 = \frac{2}{M_{11} + M_{12}/Z_{TE10} + M_{21}Z_{TE10} + M_{22}}$$

(3)

$$A = 1 - R^2 - T^2$$

(4)

For the realization of the mirror we fixed the sheet resistance R_{sm} equal to the lowest value ($R_{sm} = 30\ \Omega$/sq) reported in our previous work [10]; the lossless spacer permittivity is set equal to 5.

Figure 2(a) shows the analytical (solid lines) microwave reflectance, transmittance and absorption of our configuration when the sheet resistance of the absorbing layer R_{sa} is varied in the range 1Ω/sq to 10 kΩ/sq, while the spacer thickness is kept constant and equal to λ_g/4 (λ_g corresponds to the effective wavelength in the dielectric-loaded rectangular waveguide, and it is equal to about 16 mm at the operating frequency). For comparison, we also consider the configuration where a perfect metallic mirror substitutes the graphene mirror, corresponding to a Perfect Electric Conductor (PEC) boundary condition. This can be achieved by replacing the graphene sheet with a metallic shorting plate (e.g. thick aluminum plate), i.e., $R_{sm} \rightarrow 0$. In this particular configuration, the reflection coefficient Γ is equal to $\Gamma = (R_{sa} \| Z_{in} - Z_{TE10})/(R_{sa} \| Z_{in} + Z_{TE10})$, where $Z_{in} = jZ_{TE10,\varepsilon}\tan(\beta d)$ is the input impedance of the short-circuited line and $R_{sa} \| Z_{in}$ indicates the equivalent parallel resistance. The microwave absorption is equal to $A = 1\text{-}R = 1\text{-}|\Gamma^2|$ due to the null transmittance [Fig. 2(b)].

Analytical results were compared with 3D numerical simulations carried out by means of the Finite Element Method (COMSOL Multi-physics). Graphene was modeled by introducing a current sheet $\bar{J}_s = \sigma \bar{E}_t$ where $\bar{E}_t$ is the transverse component (x-y plane) of the electric field [10]. The simulation results are shown in Figs. 2(a) and (b) by dots.

To summarize, it is possible to deduce that these configurations lead to near-perfect absorption. Moreover, the microwave absorption can be efficiently tuned from 10% to 100% by simply varying the sheet resistance of the graphene-based absorbing layer. Finally, we note that similar behavior can be verified for plane wave illumination [14].
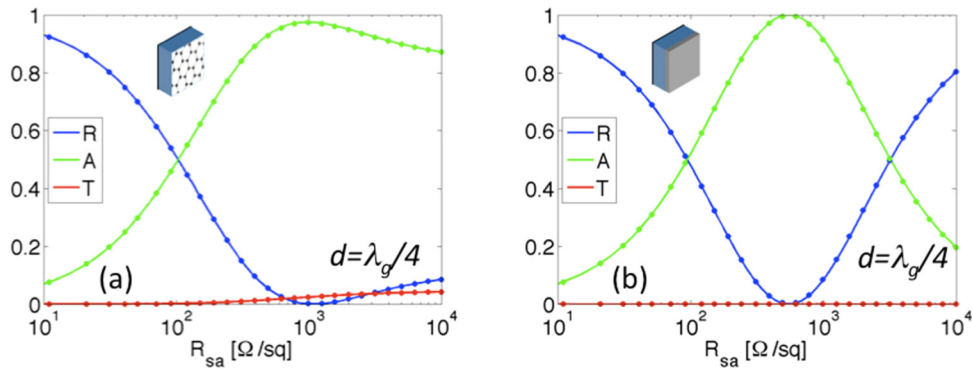
Fig. 2. Comparison between analytical (solid lines) and numerical findings (dots), in terms of microwave reflectance (blue line), transmittance (red line) and absorption (green line) of the absorbers, when the sheet resistance of the absorbing layer R_{sa} (black line in the sketch) is varied for (a) the graphene and (b) metallic mirror-based configurations, respectively. The operating frequency is equal to 9 GHz. The mirror sheet resistance is set equal to 30 Ω/sq (graphene-based mirror) and 0 Ω/sq (metallic mirror), respectively.

3. Experimental results

The absorber described in section 2 was fabricated by stacking several glass slabs having identical thicknesses, as shown in the inset of Fig. 1(b). Graphene sheets were manually transferred onto the glass substrates [10] for both absorbing and reflecting (mirror) films. Sheet resistance measurements were carried out using four-point contacts geometry in the Van der Pauw configuration on a sampled area of 4 x 4 mm^2 in air and at room temperature. In order to compare the performances of both configurations with the same sample, we fabricated a graphene absorbing layer with an average sheet resistance equal to about 400 Ω/sq. This value guarantees that the microwave absorption is higher than 90% for both graphene and metal mirror configurations. The graphene absorbing layer was realized by means of a bilayer graphene whose sheet resistance (215 Ω/sq) had been gradually increased and tuned to 400 Ω/sq by controlled hydrogenation [Figs. 3(a) and (b)]. Finally, the mirror was realized by means of a 4-layer graphene whose initial sheet resistance (in the order of 110 Ω/sq) had been decreased down to about 30 Ω/sq by SOCl$_2$ doping [10] as illustrated in Fig. 3(a).
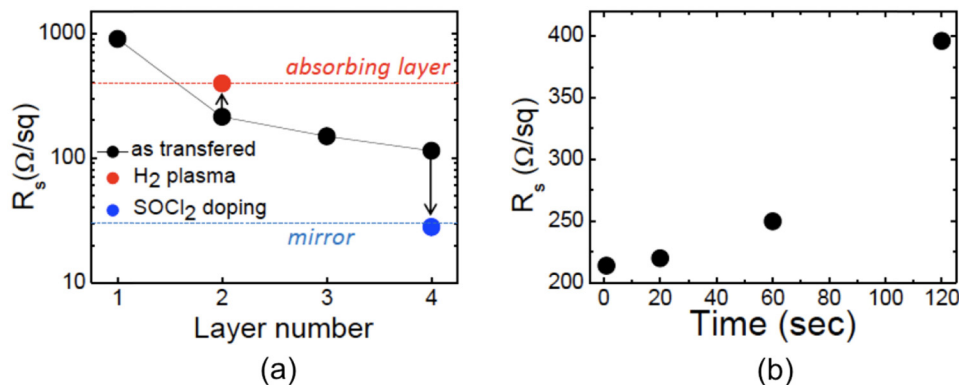

Fig. 3. (a) Sheet resistance when the layer number of graphene sheets is varied. The red and blue dashed lines correspond to the designed sheet resistances for the absorbing layer and the mirror, respectively. The black arrows indicate the modification of the sheet resistance due to the chemical protocol. (b) Graphene sheet resistance variation versus plasma-hydrogenation time.

The microwave characterization was carried out by means of a microwave setup (full description of the setup can be found in Reference [10]) with operating frequency spanning from about 8.5 GHz to 9.5 GHz.

The realization of the graphene-based microwave absorber by stacking *N* glass slabs (having identical thicknesses of 1.2 mm) defines an adaptable configuration allowing to easily modifying spacer thickness. The stacked slabs were set and blocked by means of proper clamps that avoid the presence of air gaps.

In particular, we experimentally realized two different configurations as reported in the inset of Fig. 1(b) where we employed a graphene-based (optically transparent) mirror and a metallic ("opaque" configuration), respectively.

In the former configuration, the first and the last glass slabs support the *lossy-dielectric* and the *quasi-metallic* graphene sheets respectively, while, in the latter configuration, only the first glass slab supports *lossy-dielectric* graphene. This approach leads to minimum experimental thicknesses equal to 2.4 mm (*N* = 2) and 1.2 mm (*N* = 1). The case where the spacer thickness is equal to 0 mm (metallic mirror-based configuration) simply corresponds to the waveguide capped with a metallic shorting plate.
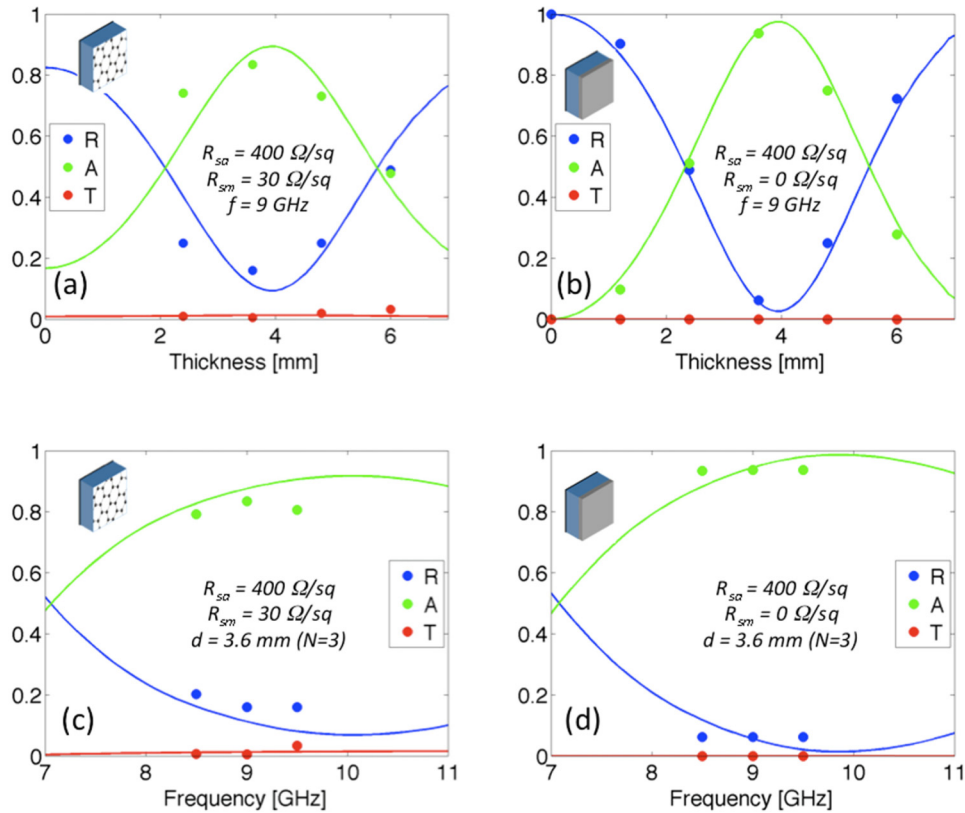

Fig. 4. (a-b) Comparison between experimental (dots) and analytical findings (solid lines), in terms of reflectance (blue line), transmittance (red line) and absorption (green line), when the spacer thickness is varied for the (a) graphene-based and (b) metallic mirror-based configurations, respectively. In (a-b) the measurements are carried out with an operating frequency equal to 9 GHz. (c-d) Comparison between experimental results and analytical findings when the operating frequency is varied for (c) graphene and (d) metallic mirror-based configurations, respectively. In (c-d) the measurements are carried out with a thickness equal to 3.6 mm (close to the quarter-wave condition).

In order to validate the theoretical predictions, we characterized these two devices by varying the spacer thickness up to 6 mm ($N = 5$) with an operating frequency equal to 9 GHz. Figures 4(a) and 4(b) compare the experimental results (dots) in terms of microwave reflectance, transmittance and absorption, with respect to the numerical findings (solid lines), showing very good agreement. For both configurations, transmittance is negligible, so that microwave absorption may be approximated by $A \approx 1$-R. The maximum achievable microwave absorption is equal to 84% and 94%, respectively, when the thickness is close to the quarter-wave condition (3.6 mm instead of about 4 mm). These findings confirm that it is possible to engineer the absorption of the graphene-based microwave absorber by properly designing the spacer thickness. In particular, the optically transparent configuration may allow microwave absorption tuning from about 20% to 90% by varying the spacer thickness.

Similar considerations may be extended for the frequency response of the graphene-based microwave absorbers. Figures 4(c) and (d) show the experimental and numerical response of the two devices when the operating frequency of the klystron is varied over its entire operating range (about 1 GHz). Also in this case, the comparison reveals good agreement between experiments and theory, and it shows almost constant microwave absorption over the frequency range of interest.

Finally, in order to verify the optical transparency of the samples we also characterized optically each device. In particular, Fig. 5(a) shows the normalized transmittance (with respect to a bare glass slab) of the layers constituting the microwave absorber in the VIS-NIR range. As inferred by the plot, the normalized optical transmittance of the absorbing layer (bi-layer graphene), mirror (four-layer graphene) and the complete absorber is equal to about 95%, 90% and 85%, respectively, at 550 nm. This is consistent with the constant absorption of the graphene layers (equal to about 2.3% times the number of graphene layers).
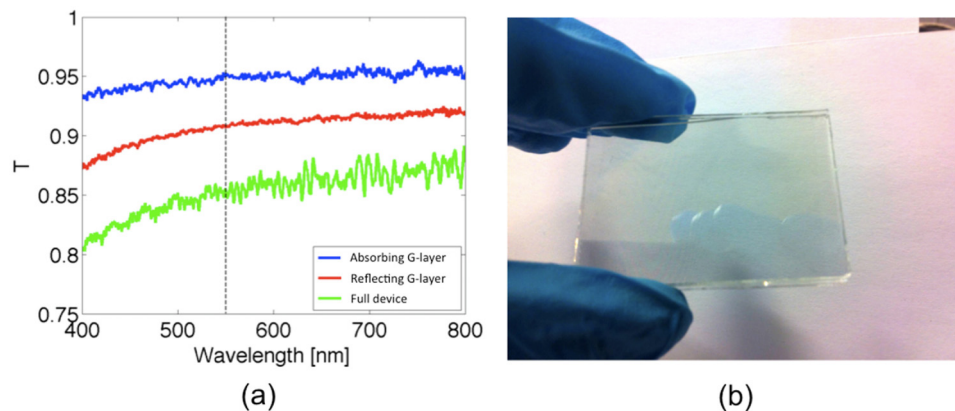

Fig. 5. (a) Normalized optical transmittance of the absorbing layer (bi-layer graphene), mirror (doped four-layer graphene) and the complete absorber, respectively. The dashed line corresponds to wavelength equal to 550 nm. (b) Picture of the realized optically transparent graphene-based absorber. On the right side, it is possible to see a slight contrast due to the presence of the graphene sheets.

4. Conclusion

In this paper, we have proposed a novel approach for the realization of an optically transparent microwave absorber consisting of a lossless spacer sandwiched between two graphene sheets (Salisbury screen configuration) whose sheet resistance is properly engineered.

The system may be described by means of an equivalent circuital model, and its performance (reflectance, transmittance and absorption) is computed by using the transfer matrix method. The analytical model predicts that it is possible to achieve near-perfect

absorption when the sheet resistance of the absorbing layer and the spacer thickness are properly designed. We also analyzed the performance of this device with respect to a similar configuration where the graphene-based mirror is replaced by a metallic mirror. The comparison reveals that the graphene-based absorber is able to achieve the performance similar to its optically opaque counterpart. Numerical simulations, carried out by means of the FEM method, confirm and corroborate the analytical outcomes.

The samples were fabricated by stacking several dielectric slabs having identical thicknesses and by properly transferring the graphene sheets onto the glass slides. The graphene sheet resistance values of the absorbing layer and the graphene-based mirror were engineered by a H_2 plasma and $SOCl_2$ doping, respectively [10].

Experimental results show that the maximum achievable microwave absorption is equal to 84% and 94% when graphene-based and metal-based mirrors are considered, respectively and the spacer thickness is close to the quarter-wave condition. Experimental measurements also reveal that absorption is nearly constant over a 1 GHz bandwidth, corresponding to the operating range of the microwave source. Finally, the optical transparency of the graphene-based microwave absorber was confirmed by measuring an optical transmittance of about 85% at 550 nm.

Our results demonstrate that it is possible to employ a single technology based on graphene in order to avoid more complex technological approaches for the realization of optically-transparent microwave absorbers. These results also prove that wide control of the electromagnetic absorption may be achieved by simply tuning the sheet resistance of the absorbing layer.

The possibility to shield and absorb microwave electromagnetic fields without affecting the optical signals is certain to yield more microwave and photonic devices with new electromagnetic and optical functionalities.