Nanostructured graphene metasurface for tunable terahertz cloaking

Pai-Yen Chen¹, Jason Soric¹, Yashwanth R Padooru², Hossein M Bernety², Alexander B Yakovlev² and Andrea Alù¹,3

¹ Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX 78712, USA
² Center for Applied Electromagnetic Systems Research (CAESR), Department of Electrical Engineering, The University of Mississippi, University, MS 38677-1848, USA

E-mail: alu@mail.utexas.edu

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Abstract. We propose and analyze a graphene-based cloaking metasurface aimed at achieving widely tunable scattering cancelation in the terahertz (THz) spectrum. This ‘one-atom-thick’ mantle cloak is realized by means of a patterned metasurface comprised of a periodic array of graphene patches, whose surface impedance can be modeled with a simple yet accurate analytical expression. By adjusting the geometry and Fermi energy of graphene nanopatches, the metasurface reactance may be tuned from inductive to capacitive, as a function of the relative kinetic inductance and the geometric patch capacitance, enabling the possibility of effectively cloaking both dielectric and conducting objects at THz frequencies with the same metasurface. We envision applications for low-observable nanostructures and efficient THz sensing, routing and detection.

3 Author to whom any correspondence should be addressed.

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1. Introduction

Graphene is a single layer of sp2-bonded carbon atoms densely packed in a honeycomb lattice \[1, 2\]. Ever since its discovery in 2004, graphene has attracted tremendous attention due to its stable thermal and mechanical properties and its special electronic properties, such as high carrier mobility and Fermi velocity \(v_F \approx 10^8 \text{ cm s}^{-1}\), quantum Hall effect, large optical transparency, mechanical flexibility, among others \[1–4\]. Graphene is considered one of the most promising material candidates for the next-generation of micro-/nano-electronic devices \[1–4\] and for solar cells and flexible flat-panel displays \[5\].

This functional nanomaterial platform has been further enriched by the discovery of its inherent plasmonic-like properties in the terahertz (THz) and infrared (IR) spectrum \[6–14\]. Graphene plasmonics has become a rapidly emerging field because of the additional possibility, unique to graphene, of gate-tuning its optical transitions and the plasmonic resonance of massless Dirac fermions. Currently, graphene plasmonics has become the subject of intensive research, with exciting applications for THz and IR tunable and switchable metamaterials \[14–18\], filters and broadband polarizers \[19\], nano-antennas \[20–22\] and optoelectronic devices \[23\], and with the ability to achieve ultrafast and broadband amplitude and phase modulations.

Plasmonic effects have been also associated to cloaking and invisibility since the beginning of the interest in applying metamaterial concepts to scattering reduction \[24\], as the anomalous polarization properties of these materials appear naturally suited to manipulate the scattering of objects. Related to this possibility, we have recently proposed a mantle cloak consisting of a simple, homogeneous graphene monolayer \[12\], which is effective in the THz spectrum. We have demonstrated that a uniform graphene monolayer may enable a wideband-tunable scattering reduction for dielectric objects. Different from bulk metamaterial cloaks based on transformation optics \[25, 26\], the physical principle behind this cloaking effect resides on scattering cancelation \[12, 13, 24, 27–32\], created by the surface current induced on the graphene monolayer that may be tailored to radiate ‘anti-phase’ scattered fields \[27–32\]. In addition to extending the mantle cloaking technique \[27\] to THz frequencies, this graphene cloak offers the advantage of being frequency-reconfigurable, enabled by its tunable surface reactance \[12, 13\]. Such a cloak may be used to potentially eliminate the cross-talk interference and noise in various THz sensing, imaging and communication systems \[12, 13\], as illustrated in figure 1(a). In this concept figure, we show a potential configuration in which a network of sensors or detectors may significantly benefit from this technology by eliminating the cross-talk between neighboring elements operating in the THz spectrum. The proposed cloak allows receiving an impinging signal without necessarily creating significant scattering around
Figure 1. Schematic representation of (a) the concept, ‘cloaking a sensor’, for cross-talk-free and low-noise sensing and communication systems and networks in [20], and (b) the THz cloaking device based on the graphene-nanopatch metasurface.

it [33], which may allow high-fidelity signal routing and reception for THz communications. Since conventional routing techniques are usually based on multiple dynamically assigned frequency channels, the additional tunability of the proposed covers may be particularly appealing.

One drawback of a graphene monolayer is that it is intrinsically inductive in the low-THz range, and is therefore not able to cloak moderately sized conducting objects, which would require a capacitive surface impedance [27, 31]. To overcome this limitation, we propose in the following a patterned graphene metasurface, which may significantly improve the performance of the graphene cloak, as discussed in the following.

Recent progress in the growth and lithographic patterning of large-area epitaxial graphene [2–4, 18] presents challenges and great opportunities for reconfigurable THz and IR metamaterials and integrated plasmonic devices. It has been theoretically demonstrated that a metasurface formed by periodic arrays of subwavelength graphene nanopatches can possess a dual inductive/capacitive surface impedance in the THz spectrum [16, 17], combining low-pass and high-pass characteristics with potential applications for THz filters and polarizers [34–36].

In this work, we investigate the performance of an atomically thin THz cloak made of a patterned graphene monolayer (see figure 1(b)), which may achieve dramatic scattering reduction for both dielectric and conducting rods, with larger flexibility compared to the homogeneous monolayer introduced in [12]. We show that the surface impedance of such graphene metasurface has a compact analytical expression, allowing us to readily design and optimize its geometry, dimensions and Fermi energy for effectively cloaking dielectric and/or conducting cylindrical objects of choice with the same metasurface. More importantly, we show that the same metasurface design may be employed to cloak drastically different objects, by properly tuning the surface impedance through the proper weighing of the kinetic inductance of graphene and the geometrical capacitance of the patterned surface.

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2. Design of a graphene mantle cloak

The surface conductivity of a graphene sheet $\sigma_s = \sigma_{\text{inter}} + \sigma_{\text{intra}}$ contains both semi-classical intraband conductivity $\sigma_{\text{intra}}$ and quantum-dynamical interband conductivity $\sigma_{\text{inter}}$. In the THz region and below the interband transition threshold, $\hbar \omega < 2 |E_F|$, $\sigma_{\text{intra}}$ dominates over $\sigma_{\text{inter}}$. Graphene’s intraband conductivity can be derived from the semiclassical Boltzmann transport equation, and in the local limit, applicable within the assumptions of this study, the conductivity is obtained as

$$\sigma \approx \sigma_{\text{intra}} = \frac{e^2 K_B T}{\pi \hbar^2 (\omega + i \tau^{-1})} \ln \left\{ 2 \left[ 1 + \cosh \left( \frac{E_F}{K_B T} \right) \right] \right\}, \tag{1}$$

where $\hbar$ is the reduced Plank constant, $e$ is the electron charge, $K_B$ is the Boltzmann’s constant, $E_F$ is the Fermi energy, $\tau$ is the relaxation time related to impurities and defects in graphene and $T$ is the temperature (here for convenience we assume a low-loss graphene with $\tau = 5 \text{ ps}$ and $T = 300 \text{ K}$; however, our additional studies show that the concepts outlined in the following may also be applied to graphene monolayers with smaller relaxation times). Throughout this study an $e^{-i \omega t}$ notation is adopted. For moderately doped graphene, $|E_F| \gg k_B T$ (e.g. pristine graphene intrinsically doped up to 0.25 eV by impurities [37]), and below the interband transition threshold, (1) reduces to a Drude-type dispersion

$$\sigma_{\text{intra}} \approx \frac{e^2 E_F}{\pi \hbar^2} \frac{\omega}{\omega + i \tau^{-1}}, \tag{2}$$

From (2), we observe that a graphene monolayer has an inductive surface impedance at low-THz: $Z_s = 1/\sigma_{\text{intra}} \approx R - i \omega L$, where $L = \pi \hbar^2 / e^2 E_F$ and $R = \tau^{-1} L$ [9, 12–14]. Moreover, different from conventional plasmonic materials, such as metals and heavily doped semiconductors, graphene’s conductivity can be controlled by shifting the electronic Fermi levels, which may be potentially tuned from $-1$ to 1 eV by chemical [38] or electronic doping [7, 8, 11].

Figure 1(b) shows the proposed graphene metasurface (a patterned graphene microtube [39]), wrapped around a dielectric or conducting rod. For a uniform plane wave normally incident to the interface, the surface impedance of a planar array of graphene nanopatches has a simple yet accurate analytical expression [17, 40–42]

$$Z_s = R_s - i X_s = \frac{D}{\sigma_s(D - g)} + i \frac{\pi}{2\omega \epsilon_0} \left( \epsilon_t + 1 \right) \frac{\sqrt{2}}{2} D \ln \left[ \csc \left( \frac{\pi g}{2D} \right) \right] \times \varphi(\alpha), \tag{3}$$

where $R_s$ is the surface resistance per unit cell related to the conduction losses, $X_s$ is the surface reactance per unit cell, $D$ and $g$ are the periodicity and gap size, respectively; $\alpha$ is the incident angle, and $\varphi_{\text{TM}}(\alpha) = 1$, $\varphi_{\text{TE}}(\theta) = 1 - \sin^2 \alpha/(2\epsilon_{\text{avg}})$ are angular correlation functions corresponding to transverse magnetic (TM)- and transverse-electric (TE)-incident polarizations, respectively [31, 32, 41, 42]; $\epsilon_t$ is the relative permittivity of the dielectric cylinder or the spacer for the conducting cylinder, and $\epsilon_0$ is the background permittivity. The second term in (3) accounts for the capacitance per unit cell of the patch array $C_E = \frac{2D}{\pi} \epsilon_0 \frac{\sqrt{\epsilon_t + 1}}{2} \ln[\csc \left( \frac{\pi g}{2D} \right)] \varphi(\alpha)$ [31, 32, 41, 42]. The first term in (3) accounts for the tunable kinetic inductance per unit cell $L_K = \frac{\ln[1/\sigma]}{\omega(1-g/D)} = \frac{\pi \hbar^2}{e^2 E_F} \frac{1}{\pi g/D}$ and the resistance per unit cell $R_G = \frac{\text{Re}[1/\sigma]}{1-g/D} = L_K \tau^{-1}$, due to the intrinsic carrier scattering; $R_G$ and $L_K$, tunable with $E_F$, are in series.

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with the geometry-yielded capacitor $C_{ES}$. As a result, the surface impedance of this ‘one-atom-thick’ graphene metasurface may be modeled with a distributed $RLC$ circuit model: $R_s = R_G$ and $X_s = \omega L_K - 1/\omega C_{ES}$. Since the kinetic inductance $L_K$ is tunable with $E_F$, we note that the surface reactance of the proposed graphene metasurface may be either capacitive or inductive, depending on the geometry, dimensions and Fermi energy. Therefore, a single metasurface can exhibit a highly controllable low-pass (capacitive) or high-pass (inductive) response. This property makes this geometry very different, and more appealing, than conventional metal-patch metasurfaces in [17, 31, 32, 41, 42], which are fundamentally capacitive.

Consider now an infinite cylinder with radius $a$ covered by a conformal graphene metasurface cloak, illuminated by a normally incident TM plane wave (see figure 1(b)). This scenario is the case of most interest for scattering reduction purposes in this geometry, as long as the cross-section is comparable to the wavelength. For a conducting cylinder, a dielectric spacer with radius $a_c$ is necessary to avoid an electrical short. We first analyze the problem using Lorenz–Mie scattering theory [43, 44], using a surface impedance boundary condition based on (3) at the surface of the graphene nanopatches. The scattering coefficients may be obtained by matching the tangential field components at the different boundaries, and may be written as [28, 29]

$$c_{TM}^n = -\frac{P_{TM}^n}{P_{TM}^n + iQ_{TM}^n}.$$  \hspace{1cm} (4)

The expressions for the $n$th order $P_{TM}^n$ and $Q_{TM}^n$ coefficients are found in [28, 29] as a function of the geometry and surface impedance. For an isotropic surface with negligible cross-polarization coupling, the total scattering width, as a quantitative measure of the overall visibility of the object at the frequency of interest, is given by [43, 44]

$$\sigma_s = \frac{4}{\kappa_0} \sum_{n=-\infty}^{n=\infty} |c_{TM}^n|^2.$$  \hspace{1cm} (5)

In the quasi-static limit (i.e. $k_0 a, k_0 a_c \ll 1$), the closed-form cloaking condition for a dielectric cylinder under TM-polarized illumination can be derived as [28]

$$X_{d\text{iel}} \approx \frac{2}{\omega \mu_0 \gamma \varepsilon_0 (\varepsilon_t - 1)},$$  \hspace{1cm} (6)

where $\gamma = a/a_c$. On the other hand, for a conducting cylinder with moderate cross-section covered by a thin spacer with relatively permittivity $\varepsilon_t$, the following cloaking condition is obtained, generalizing the results in [26]:

$$X_{\text{cond}} \approx -\omega \mu_0 a \frac{\gamma^2 - 1}{\gamma (\gamma^2 + 1)} - \frac{\omega a^3 \mu_0^2 (\gamma^2 - 1)^3}{16 \gamma^3 (\gamma^2 + 1)^3} \left[\varepsilon_0 + \varepsilon_t \varepsilon_0 (\gamma^2 - 1)/2\right]$$

$$\approx -\omega \mu_0 a \frac{\gamma^2 - 1}{\gamma (\gamma^2 + 1)},$$  \hspace{1cm} (7)

where $\mu_0$ is the permeability of background medium. It is interesting to note that the graphene metasurface in figure 1(b) needs to have a dual inductive/capacitive nature to be able to hold for (6) and (7). It is possible to achieve this property by balancing the geometric capacitance of graphene patches with the intrinsic kinetic inductance of graphene, as we discuss in the following.
Figure 2 illustrates the frequency dispersion of the surface reactance for a graphene monolayer (black-solid line) and the graphene metasurfaces I and II (red and blue solid lines). We also show the optimum surface reactance for cloaking a dielectric cylinder with $a = \lambda_0/8.4$ and relative permittivity $\varepsilon_r = 4$ (orange-dashed-dotted line) and a conducting cylinder with $a = \lambda_0/12$ covered by a thin spacer with thickness $a_c - a = \lambda_0/28$ and relative permittivity $\varepsilon_r = 4$ (green-dashed line); the operating frequency is $f_0 = c/\lambda_0 = 2.5$ THz.

3. Results and discussions

Figure 2 shows the frequency dispersion of surface reactance for (i) a uniform graphene monolayer with $E_F = 0.62$ eV (black-solid line), (ii) a graphene-nanopatch metasurface (design I) with $E_F = 0.23$ eV, $D = 6.4 \, \mu m$ and $g = 0.85 \, \mu m$ (red-solid line) and (iii) a graphene-nanopatch metasurface (design II) with $E_F = 0.3$ eV, $D = 7.6 \, \mu m$ and $g = 0.5 \, \mu m$ (blue-solid line). In the plot, we also show the optimal surface reactance, calculated using equation (4), to effectively cloak a dielectric cylinder with $a = \lambda_0/8.4$ and relative permittivity $\varepsilon_r = 4$ (i.e. silicon dioxide, SiO$_2$ or boron nitride, BN) (orange-dashed-dotted line), and using (7) for a conducting cylinder with $a = \lambda_0/12$ covered by a spacer with thickness $a_c - a = \lambda_0/28$ and relative permittivity $\varepsilon_r = 4$ (green-dotted line); here, we assume the operating frequency to be $f_0 = c/\lambda_0 = 2.5$ THz. It is observed from figure 2 that the optimum surface reactance values for cloaking agree well with the quasi-static, approximate expressions $X_{\text{dil}}$ and $X_{\text{cond}}$ in (6) and (7). Interestingly, their dispersions violate the Foster requirement of a positive slope $\partial X(\omega)/\partial \omega > 0$ for low-loss passive metasurfaces, implying that broadband cloaking may not be achieved with this or any other passive technology [45]. Still, targeting a specific design frequency (in this case $f_0$), it is possible to tune the desired surface reactance to cross the required value given by the dashed curves, and therefore maximally suppress the scattering with a single metasurface.

For instance, consistent with equation (2), a graphene monolayer always displays a purely inductive surface reactance [16], whose slope may be controlled to match the surface inductance 215.37 $\Omega$ required to cloak the dielectric rod at $f_0$, for $E_F = 0.62$ eV (solid black line in figure 2). However, there is no value of carrier concentration or Fermi energy that may allow the
solid black line, i.e. a uniform graphene monolayer, to meet the green dashed line representing the required (capacitive) surface reactance to cloak a conducting object.

On the contrary, the surface reactance of metasurfaces I and II span capacitive and inductive values, and may therefore be used to cloak either a conducting or inductive object. In addition, the patch designs require comparatively a much lower carrier concentration to achieve the optimal cloaking condition at the same frequency for the dielectric object. This is because a uniform graphene monolayer inherently requires a large $E_F$ to achieve sufficiently low surface inductance (i.e. $L_K \propto E_F^{-1}$) to meet the orange dot-dashed line. This is particularly challenging for higher frequencies, for which the optimal surface reactance gets lower and lower. However, the proposed graphene metasurface exploits the negative reactance provided by capacitive patches to compensate the high kinetic inductance of graphene with a low carrier concentration. As a result, the surface reactance may be tailored over a wide range of values, from capacitive to inductive, by tuning reasonably small values of Fermi energy. The dual capacitive/inductive graphene metasurface proposed here provides significantly added flexibility in designing cloaking devices for dielectric/conducting objects at THz frequencies.

Figure 3(a) presents the calculated scattering width for the same dielectric cylinder as in figure 2, with and without the proposed graphene metasurface cloaks (graphene monolayer and nanostructured metasurfaces). It is seen that for all cloaking devices, the scattering width may be significantly reduced at the operating frequency $f_0 = 2.5$ THz. A graphene monolayer, however, has a larger bandwidth compared to graphene metasurfaces I and II, since its dispersion slope is less steep, and follows more closely the required surface impedance curve in figure 2 (orange-dashed-dotted line). However, nanostructured graphene metasurfaces require a significantly lower doping level and provide more design flexibility. Figure 3(b), similar to figure 3(a), refers to the case of graphene metasurface I varying the Fermi energy. It is observed that the scattering width may be suppressed at different operating frequencies, tunable by shifting the Fermi energy of graphene nanopatches.

The same geometry may now also be applied to cloak the conducting rod by varying the geometry and/or Fermi energies. Figure 4(a) presents the calculated scattering width for
Figure 4. (a) Similar to figure 3(a), but for a conducting cylinder \((a = 10 \ \mu m)\) isolated by a dielectric spacer \((d_c = 14.28 \ \mu m \text{ and } \varepsilon_r = 4)\). Panel (b) is similar to figure 4(a), but for a graphene metasurface with the same geometrical parameters (period and gap) as in metasurface III and different Fermi energies.

the same conducting cylinder as in figure 2, covered by a thin dielectric spacer, with and without a graphene metasurface cloak. We show the results for metasurface I, but with Fermi energy \(E_F = 0.45\) eV (labeled metasurface III). Similarly, we designed metasurface IV with \(E_F = 0.6\) eV, \(D = 6.2\) \(\mu m\) and \(g = 0.5\) \(\mu m\) to provide the same surface reactance at the design frequency. Obviously, both geometries allow strong scattering suppression, and similar dispersion properties. The case of a graphene monolayer with \(E_F = 0.45\) eV is also presented in figure 4(a) for comparison. It is remarkable that the same metasurface geometry (designs I and III) with different Fermi energies may be used to cloak either dielectric or conducting objects at the same frequency \((f_0 = 2.5\) THz\). On the contrary, a uniform graphene monolayer would not be able to suppress any scattering for this conducting scenario, as seen in figure 4(a), since it cannot reach the optimal surface capacitance \(108.28\) \(\Omega\) given by the dashed green line in figure 2.

Although the metasurfaces III and IV have different geometries and Fermi levels, they support the same operating frequency, showing the flexibility in design offered by the proposed graphene metasurface geometry. Figure 4(b), similar to figure 4(a), refers to the case of a graphene metasurface with the same geometrical parameters (period and gap) as in metasurface I and III, but different Fermi energies. Again, it is seen that the scattering suppression is frequency-tunable by tailoring the applied Fermi energy.

We validated our theory using commercial full-wave simulations based on CST Microwave Studio (finite-integral technique [46]). Figure 5(a) presents the scattering width of a dielectric cylinder with \(a = 14.28\) \(\mu m\), \(\varepsilon_r = 4\) (figure 3(b)), with and without a graphene metasurface cover with the same geometrical parameters as in metasurface I and \(E_F = 0.37\) eV (blue line in figure 3(b)). The numerical results (solid blue line/solid circles), obtained considering the realistic nanopatch geometry of the metasurface, are in excellent agreement with our analytical formulation (solid red line/solid squares, equations (3)–(5)). Figures 5(b) and (c) respectively present a time snapshot of the electric field distribution for the cloaked and uncloaked dielectric cylinder at the design frequency \(f_0 = 3\) THz. It is clear that, by covering the object with a suitable graphene metasurface, the wavefronts of electric field can be effectively restored, as if the object is not present. On the contrary, the electric field distribution is strongly disturbed in the absence of the cloaking layer.
Figure 5. Numerical (solid blue line/solid circles) and analytical (solid red line/solid squares) comparison for: (a) scattering width of a dielectric cylinder with $a = 14.28 \ \mu m$ and $\varepsilon_r = 4$, with and without (dashed gray line/open triangles) graphene metasurface cloak, and snapshots of electric field distributions for a cloaked (b) and an uncloaked (c) dielectric cylinder.

Figure 6 is similar to figure 5, but for the conducting rod considered above. Here, the geometrical parameters of metasurfaces I and III are still used, but the Fermi energy is shifted to 0.78 eV. It is observed in figure 6(a) that the scattering width is again significantly reduced at 3 THz. It is impressive how the same graphene metasurface may effectively cloak dielectric and conducting objects with similar dimensions at the same frequency by simply tuning its Fermi energy, proving the real-time reconfigurability of this cloaking approach. We note that, by simply adjusting the geometry and doping level of graphene nanopatches, THz cloaking devices may be readily implemented for dielectric and conducting objects at the desired frequency, with interesting potential for THz communications, sensing and photodetection.

Before concluding, we note that the polarization and incidence angle may both in principle affect the cloaking effect. However, the first TM harmonic is the dominant scattering mechanism for cylinders of moderate electrical cross section, and normal incidence produces the largest total scattering cross section [29, 30]. As a result, we have focused our designs and calculations on TM impinging radiation at normal incidence. We have shown in previous papers [12, 30] how the mantle cloaking technique applied to thin cylinders is indeed robust to variations in the angle of incidence, and the results derived for infinite cylinders may be used to predict with good approximation the response of finite elongated rods [47, 48]. In addition, the capacitance yielded by the patch-array metasurface is independent of the incidence angle for TM waves, and the kinetic inductance of graphene is independent of the incident angle for both polarizations. Therefore, the proposed graphene cloak is expected to be relatively insensitive to changes in
the excitation for thin dielectric and conducting cylinders. For thicker cylinders cross-polarized coupling between TM and TE scattering occurs at oblique incidence, and mantle cloaks may require an anisotropic surface reactance to optimize the response, which goes beyond the scope of this paper.

4. Conclusion

We have proposed the use of nanostructured graphene metasurface to realize an atomically thin mantle cloak in the THz spectrum. Specifically, we have demonstrated that a graphene-nanopatch metasurface exhibits dual capacitive/inductive surface impedance, depending on the relative strength of graphene kinetic inductance and the geometric patch capacitance, which may be effectively modeled in simple analytical terms. These peculiar features open exciting venues to effectively cloak both dielectric and conducting rods with the same patterned metasurface, and reduce the requirements on required Fermi levels when using uniform graphene monolayers. The proposed metasurface is highly tunable, and may provide exciting venues in realize ultrathin, reconfigurable cloaking devices at THz frequencies, with potential applications in low-noise and cross-talk-free THz biomedical sensing and imaging systems, spectroscopy and THz communication and sensing networks, such as inter/intra-chip ultrafast links, indoor systems and wireless health applications highlighted in [20]. The recent demonstration of a cloaked photodetector based on scattering cancelation, put forward in [49], may be extended to THz frequencies with this technology, with added tunability features uniquely stemming from the graphene properties.
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References

[1] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Science 306 666–9
[2] Geim A K and Novoselov K S 2007 Nature Mater. 6 183–91
[3] Neto A H C, Guinea F, Peres N M R, Novoselov K S and Geim A K 2009 Rev. Mod. Phys. 81 109–62
[4] Lin Y M, Dimitrakopoulos C, Jenkins K A, Farmer D B, Chiu H Y, Grill A and Avouris Ph 2010 Science 327 662
[5] Wang X, Zhi L and Mullen K 2008 Nano Lett. 8 323–7
[6] Gusynin V P, Sharapov S G and Carbotte J P 2007 J. Phys.: Condens. Matter 19 026222
[7] Hanson G W 2008 IEEE Trans. Antennas Propag. 56 747–57
[8] Hanson G W 2008 J. Appl. Phys. 103 064302
[9] Lovat G, Hanson G W, Araneo R and Burghignoli P 2013 Phys. Rev. B 87 115401
[10] Rana F 2008 IEEE Trans. Nanotechnol. 7 91–9
[11] Chen J et al 2012 Nature 487 77–81
[12] Chen P Y and Alù A 2011 ACS Nano 5 5855–63
[13] Farhat M, Rockstuhl C and Bagci H 2013 Opt. Express 21 12592
[14] Vakil A and Engheta N 2011 Science 332 1291–4
[15] Koppens F H L, Chang D E and Garcia de Abajo F J 2011 Nano Lett. 11 3370–7
[16] Kaipa C S R, Yakovlev A B, Hanson G W, Padooru Y R, Medina F and Mesa F 2012 Phys. Rev. B 85 245407
[17] Padooru Y R, Yakovlev A B, Kaipa C S R, Hanson G W, Medina F and Mesa F 2013 Phys. Rev. B 87 115401
[18] Ju L et al 2011 Nature Nanotechnol. 6 630–4
[19] Bao Q, Zhang H, Wang B, Ni Z, Haley C, Lim Y X, Wang Y, Tang D Y and Loh K P 2011 Nature Photon. 5 411–5
[20] Akyildiz I F and Jornet J M 2010 IEEE Wirel. Commun. Magn. 17 58–63
[21] Carrasco E and Perruisseau-Carrier J 2013 IEEE Antennas Wirel. Propag. Lett. 12 253–6
[22] Chen P Y, Argyropoulos C and Alù A 2013 IEEE Trans. Antennas Propag. 61 1528–37
[23] Liu M, Yin X B, Ulin-Avila E, Geng B S, Zentgraf T, Ju L, Wang F and Zhang X 2011 Nature 474 64
[24] Alù A and Engheta N 2005 Phys. Rev. E 72 016623
[25] Pendry J B, Schurig D and Smith D R 2006 Science 312 1780–2
[26] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 Science 314 977–80
[27] Alù A 2009 Phys. Rev. B 80 245115
[28] Chen P Y and Alù A 2011 Phys. Rev. B 84 205110
[29] Chen P Y, Soric J and Alù A 2012 Adv. Mater. 24 OP281–OP304
[30] Soric J C, Chen P Y, Kerkhoff A, Rainwater D, Melin K and Alù A 2013 New J. Phys. 15 033037
[31] Padooru Y R, Yakovlev A B, Chen P Y and Alù A 2012 J. Appl. Phys. 112 104902
[32] Padooru Y R, Yakovlev A B, Chen P Y and Alù A 2012 J. Appl. Phys. 112 034907
[33] Alù A and Engheta N 2009 Phys. Rev. Lett. 102 233901
[34] Fallahi A and Perruisseau-Carrier J 2012 Phys. Rev. B 86 195408
[35] Nikitin A Yu, Guinea F and Martin-Moreno L 2012 Appl. Phys. Lett. 101 151119
[36] Chen P Y and Alù A 2012 Integrated infrared nanodevices based on graphene monolayers IEEE Antennas and Propagation Symp. (Chicago, IL, 8–14 July) doi: 10.1109/APS.2012.6349215
[37] Berciaud S, Ryu S, Brus L E and Heinz T F 2009 Nano Lett. 9 346–52

New Journal of Physics 15 (2013) 123029 (http://www.njp.org/)
[38] Chuang F T, Chen P Y, Cheng T C, Chien C H and Li B J 2007 Nanotechnology 18 395702
[39] Hu J Q et al 2004 Adv. Mater. 16 153–6
[40] Whitbourn L B and Compton R C 1985 Appl. Opt. 24 217–20
[41] Luukkonen O, Simovski C, Granet G, Goussetis G, Lioubtchenko D, Raisanen A V and Treyakov S A 2008 IEEE Trans. Antennas Propag. 56 1624–32
[42] Padooru Y R, Yakovlev A B, Kaipa C S R, Medina F and Mesa F 2011 Phys. Rev. B 84 035108
[43] Bohren C F and Huffman D R 1998 Absorption and Scattering of Light by Small Particles (New York: Wiley)
[44] Papas C H 1988 Theory of Electromagnetic Wave Propagation (New York: Dover)
[45] Chen P Y, Argyropoulos C and Alù A 2013 arXiv:1306.5835
[46] CST Microwave Studio 2012 www.cst.com
[47] Rainwater D, Kerkhoff A, Melin K, Soric J C, Moreno G and Alù A 2012 New J. Phys. 14 013054
[48] Alù A, Rainwater D and Kerkhoff A 2010 New J. Phys. 12 103028
[49] Fan P, Chettiar U K, Cao L, Afshinmanesh F, Engheta N and Brongersma M L 2012 Nature Photon. 6 380–5