Electronically Tunable Perfect Absorption in Graphene

Seyoon Kim,†‡ Min Seok Jang,†§ Victor W. Brar,†§,∥ Kelly W. Mauser,† Laura Kim,† and Harry A. Atwater†§

†Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, United States
‡School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea
§Kavli Nanoscience Institute, California Institute of Technology, Pasadena, California 91125, United States
∥Department of Physics, University of Wisconsin—Madison, Madison, Wisconsin 53711, United States

Supporting Information

ABSTRACT: The demand for dynamically tunable light modulation in flat optics applications has grown in recent years. Graphene nanostructures have been extensively studied as means of creating large effective index tunability, motivated by theoretical predictions of the potential for unity absorption in resonantly excited graphene nanostructures. However, the poor radiative coupling to graphene plasmonic nanoresonators and low graphene carrier mobilities from imperfections in processed graphene samples have led to low modulation depths in experimental attempts at creating tunable absorption in graphene devices. Here we demonstrate electronically tunable perfect absorption in graphene, covering less than 10% of the surface area, by incorporating multiscale nanophotonic structures composed of a low-permittivity substrate and subwavelength noble metal plasmonic antennas to enhance the radiative coupling to deep subwavelength graphene nanoresonators. To design the structures, we devised a graphical method based on effective index tunability, elucidating the origin of perfect absorption arising from critical coupling between radiation and graphene plasmonic modes. Experimental measurements reveal 96.9% absorption in the graphene plasmonic nanostructure at 1389 cm$^{-1}$, with an on/off modulation efficiency of 95.9% in reflection.

KEYWORDS: Graphene, plasmonics, perfect absorption, tunable resonance, mid-infrared, optical modulator

Over the past decade, advanced fabrication technologies have enabled enormous progress in developing nanophotonic metasurfaces for tunable optical devices through gate-tunable index-changing materials. Graphene has been the subject of intensive research as a promising candidate for tunable amplitude and phase modulation of THz and mid-infrared light. In these frequency ranges, the dielectric constant of graphene is dynamically tunable, via modulation of the carrier density under electrostatic gate control, which allows/forbids for the presence of plasmons in the graphene sheet. These plasmons display extreme light confinement, which allows the graphene sheet to be patterned at extremely small length-scales, while still interacting dynamically with longer-wavelength light. In particular, absorption strength in graphene is one of the most important measures for control of photon harvesting, and theoretical schemes have tantalizingly predicted 100% absorption in resonantly excited graphene nanostructures, indicating strong light–matter interactions in atomically thin layers.

Despite these exciting predictions and attractive features of tunable graphene nanostructures, a major obstacle for realizing perfect absorption in graphene has been the low carrier mobility in processed graphene samples due to PMMA residues and/or trapped impurities as compared with the high carrier mobilities achievable in pristine or passivated unpatterned graphene sheets, which have been assumed in theoretical works predicting unity absorption. In addition, edge defects in patterned graphene and large carrier densities required for exciting graphene plasmons also degrade effective graphene carrier mobilities. The low graphene carrier mobility gives rise to a high nonradiative damping rate, which tends to under-couple the resonant modes of graphene nanoresonator arrays. Since large-area high-performance functional graphene devices cannot rely on the high carrier mobility of exfoliated graphene flakes, achieving this performance level with graphene synthesized by chemical vapor deposition—with its attendant lower carrier mobility—is important.

One way to circumvent this issue is to increase radiative coupling to graphene nanoresonators, which is generally weak due to the inherent thinness of graphene as well as the large wavevector mismatch between graphene plasmons and free-space photons. To date, various methods, including large chemical doping carefully designed substrates, and integrated noble metal plasmonic structures, have been explored to increase coupling of radiation to graphene.

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In spite of these eforts, the realistic problems in processed graphene nanostructures have limited the maximum experimentally achievable absorption in graphene, and not even 50% absorption in graphene has been realized in the mid-infrared.

In this paper, we show the experimental demonstration of electronically tunable perfect absorption in graphene through graphene plasmonic nanostructures that exhibit dramatically higher resonant absorption, made possible by tailored nano-photonic designs that leverage the atomic thinness of graphene and the extreme confinement of graphene plasmons. First, we utilize lower-permittivity substrates, which allow better wave-vector matching between free-space photons and graphene plasmons, to improve radiative coupling to graphene plasmonic ribbons (GPRs). Second, we combine the GPRs with noble metal plasmonic metallic antennas as sub-wavelength-scale intermediaries (\(\sim \lambda_0/10\), \(\lambda_0\): free-space wavelength) to further enhance radiative coupling to deep sub-wavelength-scale GPRs (\(\sim \lambda_0/70\)).

Unlike other perfect absorbers solely relying on noble metal plasmonic effects,

\[17,32\] our structures create perfect absorption in the graphene itself by utilizing graphene plasmonic resonances, providing an ideal platform for tunable strong light–matter interactions. Of note, tunable perfect absorption is achieved with graphene nanoresonators covering less than 10% of the surface area, whereas unpatterned graphene sheets exhibit low single-pass absorption (\(\sim 2.3\%\)).

To design our plasmonic nanostructures, we devised a graphical method based on effective surface admittance. This graphical approach serves to elucidate the underlying physics of the perfect absorption in graphene and the role of other elements of our multiscale structure, revealing that perfect absorption is achieved when the graphene plasmonic nanostructure is carefully tailored to induce critical coupling to free space, i.e., matching of the admittance of graphene resonators to free space. This theoretical model reveals that perfect absorption is no longer limited by low graphene carrier mobility. As an example, we present calculations predicting perfect absorption at mid-infrared wavelengths for a graphene nanoresonator.
hole mobility as low as 200 cm² V⁻¹ s⁻¹ and at a moderate doping with the graphene Fermi level position less than −0.6 eV, which are more realistic conditions than those theoretically proposed to realize perfect absorption. Finally, reflection measurements for prototype structures demonstrate that electronically tunable resonant absorption can be increased from 24.8% to 96.9% at 1389 cm⁻¹, with an on/off modulation efficiency of 95.9% in reflection.

Figure 1 shows three designs for perfect absorption structures incorporating GPRs. All structures utilize a SiO₂/SiNx membrane with a back reflector as a base, which creates a “Salisbury screen” effect to enhance absorption in the GPRs.¹⁵,¹⁶,³³ (Supporting Information, Part 1). The type A structure depicted in Figure 1a consists of periodically arrayed 100 nm gap/100 nm wide GPRs on the SiO₂ 150 nm/SiNx 1 μm/Au substrate. The type B and C structures on the SiO₂ 150 nm/SiNx 500 nm/Au substrates in Figure 1b,c have GPRs located inside subwavelength metallic slits. In the type B structure, a 100 nm wide GPR is located in the center of a 200 nm wide metallic slit, while the metallic slit is 100 nm wide, and the 50 nm wide GPR is off to one side in the type C structure. The widths of the 80 nm thick metallic strips making up the slits in the type B and C structures are 910 and 615 nm, respectively. The total area for each structure is about 75 μm × 75 μm, and scanning electron microscope images are shown in Figure 1d–f for all structures.

The geometries of all structures were chosen in order to display maximum absorption at 1356 cm⁻¹ with graphene Fermi level below −0.6 eV, similar to the conditions for enhanced absorption that we previously reported for a conventional GPR structure on a SiNx/Au substrate,¹⁶ which we refer to here as the type 0 structure. Electric field profiles with graphene plasmonic resonance in the type A–C structures are presented in Figure 1g–l. Enhanced electric fields around the GPRs in Figure 1g–i indicate strong coupling of radiation into graphene plasmon modes. Figure 1j–l shows a collective oscillation in the type A structure due to the interaction between adjacent GPRs, and equivalent collective oscillations in the type B and C structures created by image GPRs inside the metallic strips of Figure 1b,c. The details on the equivalent collective oscillations in the type B and C structures will be discussed below.

Varying the substrate and surface environment can yield tangible benefits toward the goal of achieving perfect absorption in electrostatically gated graphene plasmonic nanostructures with lower graphene carrier mobilities. To evaluate the improvement by multiscale nanophotonic structures, we consider as a key metric the graphene carrier mobility required to achieve perfect absorption in each structure, and show that perfect absorption can be achieved with the lower graphene carrier mobilities typically seen in transferred and lithographically processed graphene. One of the fundamental problems that leads to low absorption in graphene plasmonic structures is the large wavevector mismatch between free-space photons and graphene plasmons.¹⁻³ While such a property of graphene plasmons allows miniaturizing optical
elements, it leads to inefficient radiative coupling to graphene nanoresonators. Because the dispersion relation of a transverse magnetic graphene plasmon is dependent on substrate permittivity, graphene plasmons will have a smaller wavenumber on a lower permittivity substrate, thus reducing the wavevector mismatch between free-space photons and graphene plasmons, resulting in higher radiative coupling efficiency. In addition, the reduced wavevector mismatch via a low-permittivity substrate makes the fabricated structures more robust to fabrication imperfections which cause inhomogeneous broadening. The details on the effect of a low-permittivity substrate are discussed in the Supporting Information, Part 3.

To exploit this property, SiO$_2$ layers are incorporated in the type A–C structures beneath the GPRs, while the GPRs of the type 0 structure lie on a SiN$_x$ layer possessing higher permittivity than SiO$_2$. By incorporating the low-permittivity layer, the type A structure exhibits perfect absorption for a graphene hole mobility ($\mu_h$) of 2271 cm$^2$ V$^{-1}$ s$^{-1}$, while $\mu_h = 3174$ cm$^2$ V$^{-1}$ s$^{-1}$ is required to achieve perfect absorption in the type 0 structure. Although the type A structure requires lower graphene carrier mobility for perfect absorption than the type 0 structure, such values of graphene carrier mobility are still not easily achievable in processed graphene, and this has limited experimental demonstration of electronically tunable perfect absorption in graphene. Therefore, more advanced designs requiring much lower graphene carrier mobilities are necessary for realizing perfect absorption in graphene.

The Salisbury screen structure in the type 0 and A structures improves coupling radiation into GPRs via a Fabry–Perot interference, and thus induces strongly resonant absorption in GPRs. While the back reflector has been demonstrated to enhance resonant absorption in GPRs, greater improvements can be achieved by incorporating sub-wavelength-scale intermediaries ($\sim\lambda_0/10$; $\lambda_0$, free-space wavelength), i.e., noble metal plasmonic antennas, which bridge a large wavelength mismatch between free-space photons and graphene plasmons confined in deep sub-wavelength-scale GPRs ($<\lambda_0/70$), and as a result enhance radiative coupling to graphene nanoresonators. With the noble metal plasmonic light focusing effect, the type B and C metallic slits provide field enhancement factors of 147 and 226 (Supporting Information, Part 4), respectively, while a single Salisbury screen increases the field strength by a factor of 4 in theory. The field enhancement can be increased further by widening the metallic strips. However, higher field enhancement does not always guarantee larger absorption in graphene. An optimal field enhancement exists for each structure with a given graphene carrier mobility and substrate thickness. Details will be discussed later with the description of the surface admittance model. In the type B and C structures, the SiN$_x$ thickness is adjusted to 480 nm, which is smaller in length than quarter wavelength, because the Salisbury screen resonance condition is no longer only determined by the dielectric stack thickness but also by an additional surface inductance from the noble metal plasmonic structures, as discussed below.

Figure 2a summarizes the calculated absorption in each structure at 1356 cm$^{-1}$ as a function of graphene hole mobility at the optimal graphene Fermi levels. The graphene hole mobilities required to achieve perfect absorption are 3174, 2271, 613, and 315 cm$^2$ V$^{-1}$ s$^{-1}$ for the type 0, A, B, and C structures, respectively. Compared to type 0 and A structures, perfect absorption is achievable at much lower graphene hole mobility in the type B and C structures due to the enhanced field around the GPRs, and these graphene carrier mobilities are accessible with realistic fabrication methods. The type C slit configuration exhibits a larger field enhancement than the type B slit because the narrower slit in type C more efficiently confines radiation. As a result, the type C structure achieves perfect absorption at the lowest graphene hole mobility, and the maximum absorption values with $\mu_h = 315$ cm$^2$ V$^{-1}$ s$^{-1}$ for the type 0, A, and B structures are 50.1%, 50.8%, and 91.7%, respectively, as shown in Figure 2b.

Figure 2c illustrates absorption in each component at the perfect absorption condition for the type C structure, and shows that most absorption (96.0%) occurs in the GPRs. Although graphene coverage in the type B and C structures is less than 10%, their light absorption capacities significantly overwhelm that of an unpatterned graphene sheet, while the coupled noble metal plasmonic structures contribute little to the total absorption (see the Supporting Information, Part 5, for other structures). Considering the graphene coverage area, the coupled metal structures significantly enhance interband absorption in graphene, and this is another proof of enhanced light–matter interactions in graphene in the type B and C structures. Tunable absorption maps of the type A, B, and C structures with $\mu_h = 315$ cm$^2$ V$^{-1}$ s$^{-1}$ as a function of frequency and graphene Fermi level are shown in Figure 2d–f (see the Supporting Information, Part 6, for other structures). In the absorption maps, the resonant absorption in graphene blue shifts with higher graphene Fermi level. The large absorption below 1250 cm$^2$ V$^{-1}$ s$^{-1}$ originates from phonon modes in SiO$_2$ and SiN$_x$ layers.

In addition to enhancing field strength, the metallic slits mimic the interaction between adjacent GPRs to create image GPRs inside the metallic strips shown in Figure 1b,c (Supporting Information, Part 4). When GPRs are arrayed periodically without metallic strips, the GPRs interact with adjacent GPRs, and create collective excitations, as shown in Figure 1j. The red regions in Figure 1j are due to the electric fields induced by the graphene plasmons, and the interaction between the adjacent GPRs corresponds to the blue regions. With normally incident light, the electric field in a unit cell is symmetric, and a GPR array is equivalent to a single GPR surrounded by mirror that acts as a perfect electrical conductor. Therefore, we can consider the image GPRs inside the mirror as adjacent virtual GPRs. In the type B and C structures, the metallic strips operate as mirrors for the GPRs, mimicking the interaction between adjacent GPRs, as shown in Figure 1k,l. In addition to mimicking the interaction between the adjacent GPRs, the metal edges contacting the GPRs in the type C structure reflect the near-fields induced in the GPRs, and virtually create GPRs twice as wide. As a result, the metallic strips effectively create collective modes, such that the GPRs in the type A, B, and C structures are equivalent, and accordingly all structures exhibit an equivalent graphene plasmonic resonance condition, affected by the interaction between the adjacent GPRs as well as the GPR width; however, the fields are many times stronger in the type B and C structures.

Full-wave simulations show large absorption enhancement in the proposed structures, as multiscale nanophotonic structures composed of a low-permittivity substrate and subwavelength noble metal plasmonic antennas significantly improve the radiative coupling to deep subwavelength GPRs. To fully understand the underlying photonic concepts and design the proposed structure, we develop a graphical method based on effective surface admittance, elucidating the physical origin of
the perfect absorption and the role of other elements of the proposed multiscale structure. The electromagnetic admittance is defined as the ratio of the transverse magnetic field to the transverse electric field. Admittance analysis has been widely used in electromagnetic design of multilayered stacks in response to an incoming wave. The admittance of a finite-thickness layer is usually a complex value, and the real and imaginary part of the admittance correspond to the conductance and susceptance of the layer, respectively. Here, the conductance and the susceptance represent the magnitude and the phase relation of the electromagnetic response, respectively.

Since the thickness of the graphene plasmonic nanostructures are much thinner than the free-space wavelength, the top layers can be modeled by effective surface admittance. Figure 3a,b shows the surface admittance of the type C structure with \( \mu_h = 315 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \) calculated from full-wave simulations and the surface admittance fitted by a modified susceptibility model. Using the effective surface admittance, we can calculate the absorption by evaluating the interaction between the graphene plasmonic nanostructure and the Salisbury screen. The reflection coefficient of the structure in terms of admittances normalized by air admittance (\( Y_0 \)) is derived as

\[
 r = \frac{Y_{\text{sub}} - Y_0}{Y_{\text{sub}} + Y_0} = \frac{\tilde{Y}_{\text{sub}} - 1}{\tilde{Y}_{\text{sub}} + 1} = \frac{\tilde{Y}_{\text{sub}} - 1}{\tilde{Y}_{\text{sub}} + 1} \tag{1}
\]

where \( \tilde{Y}_{\text{sub}} \) is a substrate admittance determined by the substrate geometry (Supporting Information, Part 7). Equation 1 shows perfect absorption is achieved when the surface admittance \( \tilde{Y}_s \) is equal to \( 1 - \tilde{Y}_{\text{sub}} \) and the dotted black line in Figure 3c corresponds to the \( 1 - \tilde{Y}_{\text{sub}} \) which we term a critical line, as a function of the SiN\(_x\) thickness (\( d_{\text{SiN}} \)).

This graphical approach offers an intuitive understanding of the physical origin of perfect absorption in the graphene and the role of other elements of our multiscale structure. In the surface admittance charts of Figure 3c for the type C structure, perfect absorption is achieved at a crossing of the surface admittance line and the critical line, and the maximum surface conductance is strongly dependent on the graphene hole mobility (see the Supporting Information, Part 7, for other structures). For a critical graphene hole mobility (\( \mu_h,c \)), the surface admittance and the critical lines form a single critical coupling point at a critical substrate thickness, where perfect absorption occurs. If the graphene hole mobility is lower than the critical graphene hole mobility, the surface admittance line does not cross the critical line, and it corresponds to an under-coupled regime. When \( \mu_h > \mu_h,c \), two critical coupling points exist and deviate from the critical substrate thickness (see also the Supporting Information, Part 7). In this regime, the resonance at the critical substrate thickness is over-coupled, which explains why the absorption declines after perfect absorption point in Figure 2a. Further discussion of the surface admittance can be found in the Supporting Information, Part 8.

Critical coupling can be interpreted as an admittance matching condition. Presenting the load admittance \( \tilde{Y}_L \) represented by \( \tilde{Y}_s + \tilde{Y}_{\text{sub}} \) the critical coupling condition thus corresponds to matching the load admittance to the free-space admittance. Assuming there is no absorption in the dielectric stack and assuming a perfect back reflector, the real part of the substrate admittance becomes zero, and only the imaginary part of the substrate admittance varies, depending on the substrate thickness. Here, the role of the tunable graphene plasmonic nanostructure is to adjust the load admittance so that \( \text{Re}(Y_s) = 1 \), and the nonzero imaginary part of the \( \tilde{Y}_s \) induced by the surface nanostructure is compensated by the substrate admittance, matching the load admittance to free space.
The surface admittance chart of all structures with \( \mu_h = 315 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) is shown in Figure 3d, which illustrates the important role of the coupled metallic structures. The type B and C structure exhibits more negative surface susceptance (i.e., more inductive) than the type 0 and A structures because of the strong noble metal plasmonic absorption by the interband transition in graphene. In this structure, the graphene covers 4.91% of surface area.

Figure 4. (a) Surface admittance chart of the type C structures on the SiO\(_2\) 150 nm/SiN\(_x\) substrate having different metal strip widths (blue, 615 nm; red, 918 nm) with graphene hole mobility of 200 cm\(^2\) V\(^{-1}\) s\(^{-1}\) at 1356 cm\(^{-1}\). The graphene ribbon width, the metallic slit width, and the metal thickness are 50, 100, and 80 nm, respectively, for both structures. The white, gray, and black dots in each surface admittance correspond to red, 918 nm) with graphene hole mobility of 200 cm\(^2\) V\(^{-1}\) s\(^{-1}\) and C structures due to the enhanced radiative coupling to graphene nanoresonators. We note that the net surface susceptance \( \text{Im}(\bar{Y}_{s}) \) of the type C structure is more negative (i.e., more inductive) than the type 0 and A structures, the net surface susceptance exhibited by the type 0 and A structures because of the strong noble metal plasmonic resonance induced by the subwavelength metallic slits.40,41

We can further lower the graphene hole mobility required to achieve perfect absorption by optimizing the geometry of the type C structure (Supporting Information, Part 9). The field enhancement inside the subwavelength metallic slits increases for wider metallic strips because of a larger cross-section, and leads to larger radiative coupling to graphene nanoresonators. As a result, the structure becomes more optically conductive at a given graphene carrier mobility, as shown in Figure 4a. Although we can improve the field enhancement by narrowing the metal gap width for higher intergap confinement, reducing the width of the GPRs weakens the oscillator strength, thereby degrading resonant absorption. By tailoring the geometry of the type C structure, we achieve perfect absorption with a graphene hole mobility as low as 200 cm\(^2\) V\(^{-1}\) s\(^{-1}\), as shown in Figure 4b. Other designs could allow for perfect absorption with even lower graphene hole mobility, which indicates that perfect absorption in the graphene plasmonic nanostructures is no longer limited by the low graphene carrier mobility.

To demonstrate electronically tunable perfect absorption in graphene, we measured the absorption \( \eta_{fl} = 1 - R \) for type A structures fabricated on SiO\(_2\) 150 nm/SiN\(_x\) 1 \( \mu \)m, and type B and C structures fabricated on SiO\(_2\) 150 nm/SiN\(_x\) 500 nm in a Fourier transform infrared (FTIR) microscope with a polarizer. The modulation efficiencies in reflection are calculated by \( \eta_{fl} = 1 - R/R_{max} \). Here, \( R \) corresponds to the gate voltage-dependent reflectance, and \( R_{max} \) is the reflectance when the absorption is minimized at a given graphene Fermi level between the interband absorption and the graphene plasmonic resonance.
The graphene Fermi level position is calculated using a capacitor model based on the graphene carrier density obtained from measurements of gate voltage-dependent resistance of the graphene42 (Supporting Information, Part 10).

The gate voltage-dependent tunable absorption spectra are shown in Figure 5a−c, and the corresponding modulation efficiencies ($\eta_R$) are shown in Figure 5d−f (Supporting Information, Part 11). Table 1 summarizes the measurement results for the type A, B, and C structures. In type B structures, we also observed the higher-order graphene plasmonic resonance mode,10,11 which is not easily observable in the type 0 and A structures for low graphene hole mobility (Supporting Information, Part 12). Figure 5g summarizes the absorption measurements as a function of graphene Fermi level, and corresponding modulation efficiencies are presented in Figure 5h. The measurement results indicate that the subwavelength metallic slits significantly enhance absorption in the GPRs, and both the type B and C structures display nearly perfect absorption. In particular, the type A structure reported here enables higher tunability than our previously measured type 0 structure,16 which indicates that the low-permittivity substrate improves coupling efficiency between free-space photons and graphene plasmons. In addition, the measurement results in Figure 5g show an increased baseline absorption in the type B and C structures, primarily due to the interband absorption in graphene enhanced by the plasmonic antenna effect of the metal slits, as predicted by theoretical calculations.

These mid-infrared measurements demonstrate how low-permittivity substrates and coupled subwavelength metallic slits
play pivotal roles in enhancing the resonant absorption in GPRs. In order to analyze these data further, we set the graphene hole mobilities in our simulations as a fitting parameter, and fit our simulations to the experimental modulation efficiency spectra (Supporting Information, Part 13). The fitting results reveal that the type A structure is in the under-coupled regime, and the type B structure is close to the critical coupling condition, which results in nearly perfect absorption in the later. The type C structure is expected to be in the over-coupled regime (or, the load admittance exceeds air admittance), which explains the lower absorption in the type C structure than in the type B structure in experimental measurements. Significantly, in order to enhance the resonant absorption in the type C structure, the graphene hole mobility should be decreased rather than increased to achieve the critical coupling. These results indicate that our multiscale nano-photonic designs have passed a critical threshold, whereby modulation efficiency is no longer limited by intrinsic material properties, and new, less stringent optical designs are likely possible.

We have experimentally demonstrated electronically tunable perfect absorption in graphene. Our graphical design approach enables perfect absorption in graphene even for the low graphene carrier mobility and with less than 10% of the surface area covered by graphene. In addition, our nanophotonic design for improving radiative coupling to nanostructures, based on combinations of carefully tailored multiscale resonant elements, constitutes a general approach that can achieve electronically tunable strong light–matter interactions in a broad class of both two-dimensional and thin film materials whose carrier densities and optical properties can be modulated by electrostatic gate control. The fundamental insights found here concerning interaction between metallic nanostructures and graphene have potentially far-reaching applications in graphene-based active infrared optical components, such as modulators, phased arrays, and thermal radiation management structures, as well as similar structures realized using other materials suffering from inherently weak light–matter interactions.

**Methods. Material Modeling in Simulation.** The frequency-dependent dielectric functions of SiO$_2$ and SiN$_4$ were obtained from mid-infrared spectroscopic ellipsometry, and the dielectric function of Au was taken from Palik data. Additional explanation for multiscale nanophotonic design and surface admittance, additional simulation results, and supplementary experimental results (PDF)

**AUTHOR INFORMATION**

**Corresponding Author**

*E-mail: haa@caltech.edu.*

**ORCID**

Seyoon Kim: 0000-0002-8040-9521

Min Seok Jang: 0000-0002-5683-1925

Harry A. Atwater: 0000-0001-9435-0201

**Author Contributions**

S.K., M.S.J., and V.W.B. contributed equally. S.K. and H.A.A. conceived the ideas. S.K., M.S.J., and K.W.M. performed the simulations and formulated the analytic model. S.K. fabricated the sample. S.K., V.W.B., K.W.M., and L.K. performed measurements and data analysis. All authors cowrote the paper, and H.A.A. supervised the project.

**Notes**

The authors declare no competing financial interest.

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**ABBREVIATIONS**

GPR, graphene plasmonic ribbon

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**ASSOCIATED CONTENT**

Supporting Information

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Additional explanation for multiscale nanophotonic design and surface admittance, additional simulation results, and supplementary experimental results (PDF)


