Experimental Demonstration of Total Absorption over 99% in the Near Infrared for Monolayer-Graphene-Based Subwavelength Structures

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As a novel 2D material, graphene has been studied intensively due to its outstanding optical and electronic properties.\(^\text{[1–9]}\) Graphene has the full spectrum response from the ultraviolet to terahertz band, the ultrafast response speed toward light, and the ultrahigh carrier mobility.\(^\text{[10–12]}\) which have made it an ideal material for optoelectronic devices. However, the absorption efficiency of suspended monolayer graphene toward the normal incident light is only 2.3%\(^\text{[13]}\) which limits its optoelectronic applications. In general, the resonant effect is an effective method to enhance the absorption or emission of materials.\(^\text{[14–17]}\) In the mid- and far-infrared, graphene provides strong plasmonic resonances, which have been widely exploited to enhance the absorption of graphene.\(^\text{[18–20]}\) In the visible and near-infrared, the absorption of graphene was normally enhanced by coupling graphene with dielectric\(^\text{[21–25]}\) or metallic resonant structures.\(^\text{[26–29]}\) And complete absorptions of monolayer graphene were numerically demonstrated by using critical coupling and guided mode resonance.\(^\text{[30–32]}\) In the experiment, total absorptions about 40%\(^\text{[32]}\) and 85%\(^\text{[33]}\) and graphene absorption about 77%\(^\text{[25]}\) in the visible and near-infrared were measured from monolayer graphene coupled with 1D dielectric grating or 2D silicon photonic crystals on top of a back mirror. However, higher absorption is highly desirable for high-performance graphene-based optoelectronic devices, and the experimentally realization of complete absorption for monolayer graphene based structures in the optical range is still a great challenge.

In this work, we propose a kind of monolayer graphene based absorption structures which comprise dielectric materials with low refractive index contrast, and we directly verify the complete optical absorption in experiment for monolayer graphene based subwavelength structures in the near-infrared. Peak absorptions over 99% at wavelength around 1.5 μm with full-width at half maximum (FWHM) about 20 nm are demonstrated from monolayer graphene coupled with different subwavelength gratings on top of a back gold mirror. The experimental results are in excellent quantitative agreement with the simulation results obtained by using finite-element method, which confirm convincingly the theoretical prediction of complete optical absorption for monolayer graphene in the near-infrared range.

The schematic image of the absorption structure under investigation in this work is demonstrated in Figure 1a. The structure comprises a monolayer graphene which is sandwiched between a 1D polymethyl-methacrylate (PMMA) grating and a silica layer, and a gold layer is coated in the back side of the silica layer. The absorption structure shown in Figure 1a supports several resonant modes which could be excited by outside incident waves under phase matching conditions. When the incident wave is coupled with a resonant mode, the absorption of the structure could be enhanced due to the field enhancement in the structure. And complete absorption can be obtained when the reflection wave is canceled by the emission wave of the resonant mode since the transmission can be obtained when the reflection wave is canceled by the emission wave of the resonant mode since the transmission of the structure is blocked by the gold layer.

The monolayer graphene based absorption structures shown in Figure 1a were fabricated on a silicon substrate, and an optical image of our fabricated sample is shown in Figure 1b. The fabrication processes are listed as follows. A 4 nm chromium (Cr) layer was first deposited on a 2 cm size silicon substrate by using electron-beam evaporation, and a 200 nm gold layer was deposited on the Cr layer by using magnetron sputtering. Then, a 520 nm silica layer was deposited by plasma-enhanced chemical vapor deposition on the gold layer. And next, a 1 cm size monolayer graphene (ACS MATERIAL) was transferred on the top of the silica layer. Finally, a PMMA layer was spin coated on the substrate and grating patterns with different periods were formed in the PMMA layer by using E-beam lithography. From Figure 1b we can see that the grating patterns with different periods have different diffraction colors, and the area of the sample with graphene has a slight difference in color from that of the area without graphene. The top-view scanning electron microscope (SEM) image of a fabricated pattern is shown in Figure 1c, and the white bar in the figure represents 5 μm. We measured the Raman spectrum of the monolayer graphene after the device fabrication, and compared it with the Raman spectrum of the monolayer graphene before being transferred to our sample (provided by the ACS.
MATERIAL), as shown in Figure 1d. There is nearly no D peak (around 1350 cm\(^{-1}\)) in the Raman spectrum of the monolayer graphene after device fabrication, and the spectrum is very similar with that of the graphene before transfer, so the graphene quality was preserved in the device fabrication process.

The fabricated structures were measured by our homebuilt microscope setup\(^{[34]}\) which is schematically shown in Figure 2. A tungsten-halogen source (ASBN-W050, Spectral Products) was used in the microscope setup to measure the broadband reflection spectra of the fabricated absorption structures, and a polarizer (LPNIR050, Thorlabs) was used to control the polarization of the incident light. An optical lens with focal length of 150 mm was used to focus the incident light on the absorption structures and collect the reflected light, and an optical spectrum analyzer (OSA, AQ6370B, Yokogawa) was used to measure the reflection spectra. An optical iris was used to control the incident light beam size, and the beam spot size on the sample is about 400 μm in diameter, and the divergence angle of the incident beam is less than 1°.

Figure 3a shows the reflection (R) and absorption (A) spectra of a fabricated structure with grating period \(d = \) 1254 nm for transverse-electric (TE) polarization, where the reflection spectrum was normalized by the reflected light of the 200 nm thick gold layer in the sample (assume the reflectivity of the gold layer \(R_{Au} = 98.8\%\) at the wavelength around 1500 nm according to the simulation result) and the absorption spectrum was derived based on the equation \(A = 1 - R\) since the transmission.
was blocked by the thick gold layer. As shown in Figure 3a, peak absorption over 98% with absorption FWHM of 19 nm for TE polarization was measured. In the measurement, the resolution of the OSA was chosen as 2 nm in order to enhance the signal-to-noise ratio. The absorption spectrum of the structure with $d = 1254$ nm for transverse-magnetic (TM) polarization was also plotted in Figure 3a. Since there is no resonant mode in the measured wavelength range, no enhanced absorption was observed for TM polarization, but if we form 2D patterns in the top PMMA layer, polarization-independent complete absorption could be realized. Figure 3b shows the measured absorption spectra of different fabricated monolayer graphene based absorption structures for TE polarization. Measurement results show that the peak absorptions of the structures with $d = 1230$ and 1254 nm are over 98% and the peak absorption of the structure with $d = 1270$ nm is over 97%.

An IR camera (7292M, Electrophysics) was used in the microscope setup to capture the reflection images of the absorption structures. In the measurement, the optical iris was opened enough to make the incident light beam overlap several absorption structures simultaneously. Figure 4 shows the measured reflection images of the absorption structures under the irradiation of a tunable laser (81600B, Agilent) with different wavelengths. As shown in Figure 4a–c, there was nearly no reflected light from the absorption structures for the input laser with the corresponding absorption peak wavelengths. And we can barely see the absorption structures in Figure 4d since there is no enhanced absorption for the fabricated structures at the wavelength of 1550.0 nm.

The measured peak absorptions in Figure 3 are limited by the resolution of the OSA and the divergence angle of the input light. In order to measure the peak absorptions more accurately, the tunable laser was used as the light source in the microscope setup, and the divergence angle of the input laser beam is less than 0.2°. Figure 5 shows the comparisons of

![Figure 4](image1.png)

**Figure 4.** Reflection images of the monolayer graphene based absorption structures under the irradiations of a tunable laser with different wavelengths: a) $\lambda = 1461.8$ nm, b) $\lambda = 1483.5$ nm, c) $\lambda = 1498.3$ nm, and d) $\lambda = 1550.0$ nm.

![Figure 5](image2.png)

**Figure 5.** Comparisons of reflected power from a 200 nm thick gold layer and from monolayer graphene based absorption structures with a) $d = 1230$ nm, b) $d = 1254$ nm, and c) $d = 1270$ nm for TE polarization under irradiations of the tunable laser with corresponding absorption peak wavelengths, a resolution of 0.02 nm for the OSA was selected in the measurement.
laser power reflected from a 200 nm thick gold layer and from the fabricated absorption structures for TE polarization under the irradiations of the tunable laser with the corresponding absorption peak wavelengths for the absorption structures. The resolution of the OSA was chosen as 0.02 nm in the measurement and the measured line-width of the tunable laser at each wavelength in Figure 5 was around 0.03 nm. As shown in Figure 5, the reflected peak power of the gold mirror over that of the absorption structures with \( d = 1230, 1254, \) and 1270 nm are 23.8, 20.4, and 18.5 dB, respectively. The measured results indicate that the peak absorptions of those three structures are 99.6%, 99.1%, and 98.6%, respectively.

The fabricated absorption structures are analyzed by using finite-element method-based software (Comsol Multiphysic). The dot lines in Figure 3 show the simulated spectra of the absorption structures, and the simulated results agree well with the measured results. In the simulation, the monolayer graphene was modeled as an anisotropic layer. The thickness of graphene was taken as 0.34 nm with out-of-plane refractive index \( n = 1 \) and in-plane refractive index \( n = 3 + j5.446 \lambda/3 \mu m^{-1}. \) The refractive indices of PMMA and silica were taken to be 1.48 and 1.45, respectively, and the dielectric constant of gold was given by the Drude model as \( \varepsilon(\omega) = \varepsilon_{\infty} - \omega_p^2/\left(\omega^2 + i\gamma\omega\right) \) with \( \varepsilon_{\infty} = 1.0, \omega_p = 1.37 \times 10^{16} \) s\(^{-1}\), and \( \gamma = 8.17 \times 10^{13} \) s\(^{-1}\), where the damping constant is chosen as twice of the bulk gold value. The width of the PMMA grating \( w = d/2 \). The thicknesses of the grating, the silica layer, and the gold layer were taken to be 160, 520, and 200 nm, respectively.

The complete absorption shown in Figure 3a is caused by an eigen mode in the structure, and Figure 6a shows the electric field (\( E_y \)) distribution of the eigen mode, \( E_y \) distributions in the absorption structure under normal incidence of a plane wave with wavelength of b) 1483.3 nm and c) 1550.0 nm.

The designed complete absorption structure is robust, and we can control the absorption peak wavelength by changing the grating period \( d \), while maintaining the same grating thickness and grating fill factor \( w/d \), as shown in Figure 3b. The eigen mode of the absorption structure shown in Figure 6a has a relative big mode area in the cross-section and has a relative low \( Q \) factor, which reduce its sensitivity to the structure parameters, and thus the absorption structure has relative big fabrication tolerances. Figure 7 shows the peak absorption and the absorption peak wavelength of the structure as functions...
of the grating width, grating thickness, and silica layer thickness, other parameters used in the simulation are the same as that in Figure 6. Simulation results show that the peak absorption of the structure is over 99% in the grating width range from 490 to 800 nm, the peak absorption is over 99% in the grating thickness range from 151 to 173 nm, and the peak absorption is over 99% in the silica layer thickness from 510 to 540 nm.

Until now, we investigated the characteristics of the proposed absorption structure at normal incidence. However, the angular dependence of the structure could be also interesting and important. Figure 8 shows the simulated absorption of the structure with \(d = 1254\) nm for TE polarization as functions of wavelength and incident angle. As shown in Figure 8, when the incident wave is tilted, an additional absorption peak appears in the absorption spectrum since another resonant mode is excited by the incident wave. The wavelengths of the two absorption peaks vary almost linearly with the incident angle, and this angular characteristic of the structure would be a drawback for some applications which need large incident angular tolerance, but on the other hand, it could be of potential applications for spatial optical measurement, thermal emitter, optical filter, etc.[15]

At last, we would like to investigate the effect of the monolayer graphene in the absorption structure. Since the gold layer is absorptive, a small part of the incident light will be absorbed by the gold layer in our structure, the simulated absorption spectra of the monolayer graphene and the gold layer in the structure with \(d = 1254\) nm are plotted in Figure 9a. Simulation results show that the peak absorptions of the monolayer graphene and the gold layer in the structure with \(d = 1254\) nm are 89% and 11%, respectively. However, it is hard to directly measure the graphene absorption of the structure in the experiment. As for comparison, we fabricated some grating patterns on the PMMA layer outside the graphene area in our sample. Figure 9b shows the comparison of absorption spectra of structures \((d = 1254\) nm) with and without graphene. The measured peak absorption of the structure without the graphene layer is about 40%, which is in agreement of simulation value of 36%. The minor peak shown in the absorption spectrum of the structure without graphene is caused by the divergence angle of the input light. Without the absorption of graphene, the \(Q\) factor of the resonant mode in the structure increases from 95 to 172. As shown in Figure 9, the amplitude of the electric field (|\(E|\)) in the structure without graphene under normal incidence of a plane wave with absorption peak wavelength is about 1.8 times as much as that in the structure with graphene, so the simulated peak absorption of the gold layer in the structure without graphene is over three times as much as that in the structure with graphene since the absorption is proportional to the electric field intensity (|\(E|\)^2). Although a small part of the input light was absorbed by the gold layer in our demonstrated structures, complete optical absorption for monolayer graphene could be achieved if we replace the gold layer with a lossless dielectric mirror.

In conclusion, peak absorptions over 99% with FWHM about 20 nm in the near-infrared were measured for monolayer graphene coupled with subwavelength gratings on top of a back gold mirror. The demonstrated absorption structures with total thickness less than 1.0 \(\mu m\) are very compact, and the absorption peak wavelength of the structure can be easily controlled by changing the geometric parameters of the structure. Because of their high absorption efficiency and loose

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**Figure 8.** Simulated absorption of the monolayer graphene based absorption structure with \(d = 1254\) nm for TE polarization as functions of wavelength and incident angle.

**Figure 9.** a) Simulated absorption spectra of the monolayer graphene and the gold layer in the absorption structure with \(d = 1254\) nm for TE polarization. b) Measured absorption spectra of structures \((d = 1254\) nm) with and without graphene, and the dot line shows the simulated absorption spectra of the structure without graphene. c) Normalized electric field amplitude distributions of the structures with and without graphene under normal incidence of a plane wave with absorption peak wavelength.
fabrication requirements, the demonstrated structures may provide practical applications for graphene and other 2D material based optoelectronics devices, such as high efficiency photodetectors and high extinction ratio modulators.

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