Efficient Modulation of 1.55 μm Radiation with Gated Graphene on a Silicon Microring Resonator

Ciyuan Qiu,†§ Weilu Gao,†§ Robert Vajtai,‡ Pulickel M. Ajayan,‡ Junichiro Kono,†‡§ and Qianfan Xu‡§†

†Department of Electrical and Computer Engineering, ‡Department of Materials Science and NanoEngineering, and §Department of Physics and Astronomy, Rice University, Houston, Texas 77005, United States

ABSTRACT: The gate-controllability of the Fermi-edge onset of interband absorption in graphene can be utilized to modulate near-infrared radiation in the telecommunication band. However, a high modulation efficiency has not been demonstrated to date, because of the small amount of light absorption in graphene. Here, we demonstrate a ≈40% amplitude modulation of 1.55 μm radiation with gated single-layer graphene that is coupled with a silicon microring resonator. Both the quality factor and resonance wavelength of the silicon microring resonator were strongly modulated through gate tuning of the Fermi level in graphene. These results promise an efficient electro-optic modulator, ideal for applications in large-scale on-chip optical interconnects that are compatible with complementary metal-oxide-semiconductor technology.

KEYWORDS: Graphene photonics, NIR modulator, silicon microring resonator, high on/off ratio

Large-scale integration of nanoscale electro-optic modulators with high efficiencies and speeds is a key technology required for future optical communications and computing. Achieving high efficiencies is a challenging goal because of the inherently short light-matter interaction lengths in nanoscale photonic circuits. Therefore, there are currently worldwide efforts in finding new materials with ultrastrong electro-optic effects or novel schemes for effectively enhancing light intensities within a small volume.

Graphene, a sheet of carbon atoms in a hexagonal lattice with photon-like massless and gapless electrons, strongly couples with light with universal, wavelength-independent interband absorption (~2.3% per layer) in the visible range. This universal absorption can be suppressed, or Pauli blocked, when 2E_f > E_p, where E_f is the Fermi energy and E_p = ℏω is the photon energy. In the communication band, the wavelength, λ, of light used is 1.55 μm (or 0.86 eV in photon energy), thus, interband absorption in graphene is blocked if E_f > 0.43 eV and can be tuned through electric gating. Such ultrawideband tunability makes graphene a promising platform on which to build active optoelectronic devices for high-speed communications. Graphene-silicon hybrids have been used recently for electro-optic modulators operating in the telecommunication band, including a silicon waveguide structure and a photonic crystal cavity. However, they either have a low switching contrast ratio (0.1 dB/μm) or a relatively low quality factor, which limits their applicability to large-scale on-chip interconnections.

Here, we combine graphene with a silicon microring resonator to demonstrate a high-efficiency electro-optic modulation through the evanescent mode coupling between graphene and silicon. Microring resonators have been used in various optoelectronic devices, including electro-optic modulators, filters, and sensors. Electro-optic modulation is usually achieved by tuning the resonance wavelength, λ_m, through free carrier plasma effects in silicon. It has a small footprint, large extinction ratios, and a very high quality factor, and is suitable for large-scale optical interconnections providing a good platform for integrating graphene. Even with a single atomic layer, graphene can exhibit strong light-matter interactions and have a significant effect on the resonator due to the great tunability of the Fermi level. We developed a highly efficient electro-optic modulator with a modulation depth of about 40%, which will be useful in large-scale on-chip optical interconnects for optical communications, logic computing, and sensing.

Results. Figure 1a,b shows schematic diagrams of the graphene-silicon hybrid structure that we fabricated. The Fermi level of graphene, and thus, the effective index of the hybrid structure, is tuned by applying a voltage between the electrodes on graphene and the doped-region electrodes with Al2O3 gating dielectrics, as shown in the cross-section of the device (Figure 1b). Figure 1c shows a scanning electron micrograph of the fabricated microring resonator after graphene transfer (see Methods). The graphene layer was characterized using Raman spectroscopy, as shown in Figure 1d. The locations of the G and 2D peaks, the single Lorentzian shape of the 2D peak, the 2D/G intensity ratio, and the near absence of the D peak all indicate a high-quality single layer graphene sample after the transfer and fabrication processes.

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Figure 2a shows transmission spectra for devices without graphene (solids lines) and with graphene (dashed lines) with different gap distances between the waveguide and ring resonator. The smallest gap we could achieve was limited by the fabrication process to be 200 nm. Without graphene, the device with a gap of $\sim 200$ nm is close to the critical coupling condition and has an extinction ratio greater than 10 dB. The other two devices with larger gaps are under-coupled, and the extinction ratio becomes smaller as the gap increases. With monolayer graphene integrated, the line width increases and the extinction ratio decreases. It shows that the photon lifetime in the cavity decreases due to interband absorption in graphene.

On the basis of the classical photonic circuit model, the transmission spectra can be fit with

$$T(\lambda) = \frac{(t - e^{-\kappa^2/2})}{(1 - t e^{-\kappa^2/2})}^2$$

(1)

where $t = (1 - \kappa^2)^{1/2}$, $\kappa$ is the coupling coefficient between the straight waveguide and the ring resonator, and $e^{-\kappa^2}$ and $\phi(\lambda)$ are

Figure 1. (a) Schematic diagram of graphene-modulated silicon microring modulator. (b) Cross-sectional diagram of the modulator corresponding to the red dashed line in (a). $\text{Al}_2\text{O}_3$ works as the gate dielectric material. The gate voltage is applied between the bottom $n^+$-doped silicon slab and graphene layer. (c) Top-view scanning electron microscope picture of the modulator after graphene is transferred on top of the microring area. (d) Raman spectrum of transferred graphene.

Figure 2. (a) Transmission spectra for devices with different gaps. The solid lines show the spectra without graphene and dash lines show the spectra with graphene. (b) Calculated intrinsic quality factors. (c) Calculated coupling quality factors.
the loss and phase delay, respectively, in the cavity per round; the loss is determined by the imaginary part, \( n_\text{eff} \). From this model, together with the coupled mode theory,\(^{28}\) we determined the intrinsic quality factor (\( Q_i = 2\pi n_\text{eff} R / \lambda_0 \)) to be \( \sim 5000 \) and the coupling quality factor (\( Q_c = 4\pi n_\text{eff} R / \lambda_0 \kappa^2 \)) to range from \( \sim 7500 \) to \( \sim 25000 \), as plotted versus gap value in Figure 2b,c, respectively. Here, \( \lambda_0 \) is the resonance wavelength, \( R \) is the ring radius, and \( n_\text{eff} \) is the group index of the cavity. After graphene integration, \( Q_i \) is decreased to \( \sim 1300 \), suggesting that the loss from graphene dominates the photon lifetime in the cavity while the coupling quality factor does not change much, as expected. Also, from the difference in loss in the ring cavity between before and after graphene integration, we estimated the loss in graphene to be \( \sim 200 \, \text{dB/cm} \) for all three devices, which is 2 orders of magnitude higher than the intrinsic loss of a typical silicon waveguide.

Figure 3a shows transmission spectra at different gate voltages, \( V_g \), for a microring resonator with graphene with a gap width equal to 200 nm. Figure 3b shows the corresponding transmission spectra change at different \( V_g \). Specifically, this figure shows the change in transmission due to the applied gate voltage, that is, differential transmission, \( \Delta T / T_0 \) where \( \Delta T = T(V_g) - T_0 \) is the difference between the transmission value under a certain gate voltage (\( V_g \)) and that without any applied gate voltage, \( T_0 \). With increasing \( V_g \), the resonance width decreases, and the extinction ratio increases. It is seen that \( \Delta T \) is positive on the longer-wavelength side of the resonance due to the blue shift of the resonance with increasing \( V_g \). The \( V_g \) dependence of transmission at a wavelength of 1555.97 nm is shown in Figure 3c. The transmission at \( V_g = 6 \, \text{V} \) is about 60\% of that at \( V_g = 0 \, \text{V} \), corresponding to a modulation depth of \( \sim 40\% \). The measured spectra were fit with eq 1 to extract the \( \lambda_0 \) and \( Q_i \) values while the \( Q_c \) value did not change with \( V_g \). Figure 3d,e shows, respectively, \( Q_i \) and \( \lambda_0 \) (compared with the 0 V resonance wavelength) as a function of \( V_g \). An increasing \( V_g \) elevates the \( \epsilon_p \) of graphene to lower interband absorption through Pauli blocking, which in turn increases the photon lifetime in the cavity and the quality factor. As shown in Figure 3e, either an increase or decrease in \( V_g \) blue shifts the resonance wavelength, suggesting that the real part of the dielectric constant of graphene peaks around \( V_g = 0 \, \text{V} \) and thus any bias lowers the effective index of the waveguide.\(^{11}\)

To confirm that the blue shift of \( \lambda_0 \) and the increase of \( Q_i \) of the ring resonator with increasing \( V_g \) are solely due to the graphene layer, we developed a theoretical model to quantitatively explain the experimental observations. Gate-dependent complex dielectric constants of graphene have been extensively studied within the random phase approximation and using the Kramers–Kronig relations.\(^{11,29,30}\) The imaginary part, \( \epsilon''_g \), is characterized by interband and intraband absorption while the real part, \( \epsilon'_g \), can be obtained from \( \epsilon''_g \) by using the Kramers–Kronig relation. The complex dielectric constant of graphene has the following form\(^{11}\)

\[
\epsilon'_g(E_p) = 1 + \frac{\epsilon^2}{8\pi\epsilon_0\epsilon''_0 d} \ln \left( \frac{E_p + 2|E_l|}{E_p - 2|E_l|} \right)^2 + \frac{\pi E_p^2}{|E_l|^2} \sum \frac{1}{\tau_i} \\
= \frac{\epsilon^2}{4\pi\epsilon_0\epsilon''_0 d} \ln \left( \frac{E_p - 2|E_l|}{E_p + 2|E_l|} \right)^2 + \frac{1}{\tau_i} \\
+ \frac{\epsilon^2}{4\pi\epsilon_0\epsilon''_0 d} \frac{|E_l|^2}{E_p^2 + \frac{1}{\tau_i}} \\
\]

\[
\epsilon''_g(E_p) = \frac{\epsilon^2}{4\pi\epsilon_0\epsilon''_0 d} \left[ 1 + \frac{1}{\pi} \tan^{-1} \left( \frac{E_p - 2|E_l|}{\Gamma} \right) - \tan^{-1} \left( \frac{E_p + 2|E_l|}{\Gamma} \right) \right] \\
+ \frac{\epsilon^2}{4\pi\epsilon_0\epsilon''_0 d} \frac{|E_l|^2}{E_p^2 + \frac{1}{\tau_i}} \\
\]

where \( d \) is the thickness of graphene (0.5 nm),\(^{31}\) \( \Gamma \) is the interband line width broadening (set to be 160 meV through...
fitting the measured spectra), and the free carrier scattering rate $1/\tau$ can be neglected as it is much smaller than the incident photon frequency, $\omega$.

By using eqs 2 and 3 above to fit the experimental data, we can get the relationship between the $n_{\text{eff}}$ of the waveguide and graphene’s $E_F$. Figure 4a shows spectra at different gate voltages together with fitting curves, and Figure 4b shows the extracted $E_F$ value versus $V_g$. When $V_g$ increases from 0 to 6 V, $E_F$ increases by $\sim$66 meV, lowering both the real and imaginary parts of graphene’s dielectric constant so that $\lambda_0$ blue shifts and the photon lifetime becomes longer. However, when $V_g$ is negative, the quality factor change is negligibly small (Figure 3d) although there is a small but noticeable blue shift (Figure 3e). Because of the relatively high amount of p-doping combined with the relatively low quality of our oxide layer, we cannot shift the Fermi energy from the p-region into the n-region; the dielectric breaks down before we reach the n-region. Furthermore, the residual carriers from carrier puddles in the transferred graphene combined with the relatively low quality of our oxide may cause a much smaller shift in $E_F$ (Figure 4b). This smaller shift in $E_F$ also yields a tiny modulation at negative $V_g$ as shown in Figure 3c.

Our graphene-based microring modulator can potentially operate at tens of gigahertz. In this structure, graphene only needs to be present on top of the microring resonator to have an effect. The modulation speed is limited by the $R_s C$ of the circuit, where $R_s$ and $C$ are the resistance and capacitance of the device, respectively. In our scheme, the fundamental limitation of the device resistance mainly comes from the graphene resistance and the contact resistance; the former is typically several hundred kilo-ohms in our devices, and the latter is several ohms. However, one can reduce the graphene resistance by extending the electrical metal connection to the microring resonator. A very tight gap about $\sim$1 $\mu$m can in principle be obtained, which will be necessary to eliminate any absorption in the metal. Furthermore, the graphene sheet resistance can be as low as $\sim$125 $\Omega$/sq in a highly doped region. Thus, the graphene serial resistance can be reduced to a few ohms. The capacitance due to the graphene layer can be calculated as $C = \varepsilon_0 \varepsilon_d A_{\text{gr}}/d \approx 0.1 \text{ pF}$ in the tight gap configuration, where $\varepsilon_d (=9.34)$ is the relative permittivity of $\text{Al}_2\text{O}_3$, $\varepsilon_0$ is the vacuum permittivity, and $d$ (= 25 nm) is the thickness of $\text{Al}_2\text{O}_3$. Hence, the speed, taken as $1/2\pi R_s C$, can be as large as $\sim$80 GHz by taking $R_s \sim 20 \Omega$.

In conclusion, we have demonstrated an active microring modulator based on graphene. By using this high-$Q$ resonator, strong amplitude modulation with a depth as large as $\sim$40% was achieved. By improving the quality of the dielectric layer, we should be able to tune the Fermi level of graphene in a wider range, which will in turn significantly enlarge the modulation depth to $>$10 dB. Its operation speed is also expected to be up to tens of gigahertz by better device fabrication and higher graphene quality. Its footprint can be significantly reduced to fit large-scale on-chip interconnections, which will find applications in optical communications, imaging, signal processing, and sensing.

Methods. Device Fabrication. The microring resonator was initially fabricated using the OPSIS service, through a CMOS photonics foundry at the Institute of Microelectronics of Singapore. The fabrication process started with a silicon-on-insulator wafer, consisting of a 220 nm thick top silicon layer and a 2 $\mu$m thick buried oxide layer. Rib waveguides with a 300 nm width, 220 nm height, and 90 nm slab thickness were used to construct the photonic circuit, in which only quasi-TE mode was supported. A microring resonator with a diameter of 10 $\mu$m was side-coupled to the straight waveguide. Inverse tapers with 180 nm wide tips were integrated for input and output terminals of the waveguide to enhance the coupling between the waveguide and tapered lens fibers. A deep-UV lithography process was used first to define the device pattern, which was then etched into the silicon layer by inductively coupled plasma etching. Following the etching process, an n$^+$-doping region was formed outside the ring, as illustrated in Figure 1b, by patterned ion implantation. The gap between the n$^+$-doping region and the ring waveguide was set to be 1.5 $\mu$m to eliminate any effect of the gate voltage on the silicon waveguide. A 2.1 $\mu$m thick SiO$_2$ layer was then deposited onto the wafer using plasma-enhanced chemical vapor deposition. Then vias were opened on the implanted area, and a 2 $\mu$m thick aluminum layer was sputtered and etched to form electric connections to the doping region. A 1.8 $\mu$m dry etch and 0.5 $\mu$m wet HF etch was followed to open a bare silicon area in the device region. We then deposited a 25 nm layer of $\text{Al}_2\text{O}_3$ in the bare silicon area as the electrostatic gating by using electron beam evaporation. Chemical vapor deposition (CVD) grown graphene on a copper foil was transferred onto this device using standard transfer techniques. The transferred graphene layer was typically p-doped. Graphene was then patterned by electron beam lithography and oxygen plasma to avoid contact with the aluminum pad on the n$^+$-doping region. The perimeter of the ring is about 31.4 $\mu$m, and the effective area covered by graphene is 15.7 $\mu$m$^2$. Finally, a 30 nm Ti/Au electrode on graphene was deposited through electron-beam lithography and a lift-off process.

Graphene Transfer. The graphene layer was grown by CVD on copper foil and then transferred onto a SiO$_2$/Si substrate.
using a poly(methyl methacrylate) (PMMA)-assisted wet-transfer technique. In this transfer process, first a PMMA layer was spin-coated on graphene on the copper foil, and the copper foil was then etched away in ferric chloride (FeCl₃) solution. The PMMA—graphene film floating on the etchant was moved to distilled water several times to rinse the etchant residue and then scooped by the substrate. The chip was dried in air overnight, and the PMMA was removed by acetone and the whole chip was cleaned by isopropyl alcohol.

**AUTHOR INFORMATION**

**Corresponding Author**
*E-mail: qianfan99@gmail.com.*

**Author Contributions**
C.Q. and W.G. contributed equally to this work.

**Notes**
The authors declare no competing financial interest.

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