Supporting Information

Low insertion loss plasmon-enhanced graphene all-optical modulator

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S1 Propagation Modes: TM vs TE

The polarization of the excitation waveguide mode has a significant impact on the effective optical absorption of graphene. Figure S1 illustrates the quasi-TM and quasi-TE modes of the SOI waveguide with graphene on top. Graphene absorbs $\sim 2.5 \times$ more light when the excited mode is TM-like. The propagation modes were computed using Lumerical MODE.

![Figure S1: (a) Quasi transverse-magnetic and (b) quasi transverse-electric modes of the graphene on SOI waveguide. The dashed white line represents the graphene sheet plane. $\alpha$ is the propagation loss due to graphene. $\lambda = 1550$ nm.](image)

S2 Absorption Efficiency

The Au stripe enhances the effective absorption of graphene, yet it introduces inevitable ohmic losses. We varied the stripe width and recorded $\alpha_{Gr}$ (see Figure S2a), following the approach that was described in the Methods section of the main text. $\alpha_{Gr}$ is maximized when the stripe width is 380 nm, where $\alpha_{Gr} = 0.09 \text{ dB/\mu m}$. This is $\sim 4 \times$ higher than the absorption of graphene without a stripe, which is only 0.024 dB/\mu m (see Figure S1a).

To further ensure that $\alpha_{Gr}$ is maximized with respect to $\alpha_{total}$, we plotted the absorption efficiency $\alpha_{Gr}/\alpha_{total}$ as a function of the stripe width (see Figure S2b). The highest absorption efficiency is obtained when a 380 nm wide stripe is placed on top of graphene. The low
absorption efficiency at small widths may indicate that the Au stripe is not large enough to induce a strong plasmonic enhancement of the electric field at the graphene sheet plane. On the other hand, widening the stripe beyond 380 nm also reduces the absorption efficiency. This could be related to the mode distribution, where the plasmonic enhancement is concentrated at the stripe edges, which happens to be far from the waveguide center, where most of the optical power is present. We show the mode distribution for a 480 nm wide stripe in Figure S3. The plasmonic response of a gold nanostructure is strongly dependent on its morphology, and is strongly enhanced at sharp corners and edges. Due to the strong concentration of the electric field at the edges of the stripe, the coupling efficiency degrades when its width increases (see Figure S2b). Therefore, for this device, a wider stripe yields lower absorption and coupling efficiencies.

**S3 Taper Absorption**

The absorption of the graphene sheet beneath the taper can be simply calculated by dividing the waveguide into four quarters, as is shown in Figure S4. For graphene on top of silicon
Figure S3: Quasi transverse-magnetic mode of the modulator waveguide with a 480 nm wide Au stripe. The dashed white line represents the graphene sheet plane. $\lambda = 1550$ nm.

(quarters 1 & 4), the absorption is taken as 0.024 dB/µm, based on the results obtained in section S1. For the graphene portion beneath the Au taper, its absorption is calculated using the approach that is described in the Methods section of the main text. The ohmic loss due to Au is also considered based on the same approach. The taper is 600 nm long, and therefore, the absorption in each quarter is effectively taken for one-fourth of the taper-waveguide length, namely 150 nm.

Figure S4: The taper-waveguide section divided into four quarters.

S4 Broadband Response

The refractive index of Au was taken as $n_{Au} = 0.35755 + 10.669i$ at $\lambda = 1550$ nm, based on the data given in ref. $^3$ for a 21 nm thick Au. Figure S5a presents the refractive index
data of Au at other wavelengths, also taken from the same reference. Similar simulations and calculations were performed at other wavelengths. The computed coupling efficiency, total loss, and gold loss are shown in Figure S5b, as a function of λ. The coupling efficiency decreases with λ, since the propagating mode size becomes larger, leading to a reduction in the power overlap between the SOI mode and the modulator section. The propagation losses, α\text{total} and α\text{Au}, are also affected by the mode size variation with respect to λ. In addition, the excitation wavelength affects the absorption properties of a plasmonic nanostructure. Therefore, the propagation loss dependence on λ is not as monotonic as it is the case for the coupling efficiency.

![Figure S5](image)

Figure S5: (a) Refractive index data of 21nm thick gold. (b) Total loss, gold loss, and coupling efficiency as a function of wavelength.

Fig S6 shows \(U_{sw}\) and \(U_{eff}\) as a function of the pump signal wavelength for \(\mu = 0.1\,\text{eV}, \mu = 0.15\,\text{eV},\) and \(\mu = 0.2\,\text{eV}.\) It is noted that \(U_{eff}\) follows the trend of \(U_{sw},\) except at shorter wavelengths, where the absorption efficiency (see Figure S7) and the coupling efficiency (see Figure S5b) are maximized, leading to a smaller \(U_{eff}.\) The higher absorption efficiency that is obtained at shorter wavelengths could be a result of the smaller mode size, which makes its interaction with the Au stripe weaker, hence boosting the absorption efficiency of graphene.
Figure S6: (a) Switching energy ($U_{sw}$), and (b) effective switching energy ($U_{eff}$) as a function of the pump signal wavelength ($\lambda_{pump}$), for $\mu = 0.1 \text{ eV}$, $\mu = 0.15 \text{ eV}$, and $\mu = 0.2 \text{ eV}$.

Figure S7: Absorption efficiency of graphene ($\alpha_{Gr}/\alpha_{tot}$) as a function of wavelength.

Because of the aforementioned variations in the absorption efficiency and coupling efficiency as functions of wavelength, the extinction ratio (ER) and the insertion loss (IL) are also functions of wavelength, as is shown in Figure 7a in the main text. Figure S8 shows the resulting ER/IL ratio as a function of wavelength. It is noted that the data pattern in Figure S8 is very similar to Figure S7, which indicates the importance of the absorption efficiency in determining the ER/IL ratio.
S5 Fabrication Methods

Without a taper, the coupling efficiency was computed to be $\sim 77\%$ at $\lambda = 1550\,\text{nm}$. Considering that the Au stripe may be misaligned by a typical $\sim 20\,\text{nm}$ stitching error,$^{5,6}$ the coupling efficiency slightly drops to become $76\%$. In practice, the taper tip cannot be infinitely sharp; it is expected instead to be more rounded as illustrated by the dashed line in Figure S9. The computed coupling efficiency with a rounded tip is $84.5\%$ at $\lambda = 1550\,\text{nm}$. Therefore, a rounded tip does not have a detrimental impact on the coupling efficiency. Taking into account a routinely obtained etch depth variation of $\pm 5\,\text{nm}$ into the slab thickness height, the SOI waveguide would still satisfy the single-mode condition. By using state-of-the-art fabrication technologies, wafers with $\pm 7.6\,\text{nm}$ linewidth uniformity and $\pm 1\,\text{nm}$ thickness uniformity can be achieved.$^7$ Such variations have a negligible impact on the coupling efficiency, and do not affect the single-mode condition.

The side SiO$_2$ layers can be introduced into the structure using local oxidation of silicon (LOCOS), where the waveguide top surface is masked by a silicon nitride (SiN) layer, while wet oxidation is performed on the surrounding silicon.$^8$–$^{11}$ Due to process variations, the side oxide thickness might not exactly match the silicon ridge height.
Figure S9: The dashed line represents the geometry of the simulated rounded tip.

In Figure S10, we study the impact of SiO$_2$ layers that are 90 nm higher than the silicon waveguide. Graphene is placed only on top of silicon in Figure S10b, since graphene cannot be curved in Lumerical. This is a reasonable approximation since most of the waveguide mode is located in the center, away from the SiO$_2$ layers. The computed coupling efficiency between the two modes shown in Figure S10 is 77%, and the computed propagation loss in Figure S10b is 0.43 dB/μm. Both results are similar to the ideal case where the SiO$_2$ layers are 500 nm thick. Therefore, variations in the SiO$_2$ height are negligible, which is an expected result since the side SiO$_2$ is not absorptive in this wavelength region, and has a relatively low refractive index in comparison to silicon.

Figure S10: (a) Simulation of the SOI waveguide with 590 nm thick SiO$_2$ layers. (b) Same structure as in (a) with graphene and Au placed on top of silicon. $\lambda = 1550$ nm, TM-mode.
S6  Modeling Parameters

We modeled graphene in Lumerical as a 2D material with a surface optical conductivity ($\tilde{\sigma}$) given by: \(^{12,13}\)

$$\tilde{\sigma}(\omega, \Gamma, \mu, T) = \tilde{\sigma}_{\text{intra}}(\omega, \Gamma, \mu, T) + \tilde{\sigma}_{\text{inter}}(\omega, \Gamma, \mu, T)$$  \(1\)

$$\tilde{\sigma}_{\text{intra}}(\omega, \Gamma, \mu, T) = \frac{-j e^2}{\pi \hbar^2 (\omega + j2\Gamma)} \int_0^\infty E \left( \frac{\partial f(E)}{\partial E} - \frac{\partial f(-E)}{\partial E} \right) dE$$  \(2\)

$$\tilde{\sigma}_{\text{inter}}(\omega, \Gamma, \mu, T) = \frac{-j e^2 (\omega + j2\Gamma)}{\pi \hbar^2} \int_0^\infty \frac{f(-E) - f(E)}{(\omega + j2\Gamma)^2 - 4(E/\hbar)^2} dE$$  \(3\)

$$f(E) = (e^{(E-\mu)/k_B T} + 1)^{-1}$$  \(4\)

where $\tilde{\sigma}_{\text{intra}}$ and $\tilde{\sigma}_{\text{inter}}$ account for the surface optical conductivity due to intraband and interband transitions, respectively. $\omega$ is the angular frequency of incident photons, $\Gamma$ is the scattering rate of graphene, $T$ is the operation temperature, $e$ is the electron charge, $\hbar$ is the reduced Planck constant, $f(E)$ is the Fermi-Dirac distribution, and $k_B$ is the Boltzmann constant. We set the chemical potential to 0.15 eV and the scattering time to 1 ps. Since graphene’s absorption is dominated by interband transitions at telecom wavelengths, variations of the scattering time (or rate) have a negligible impact on the absorption.\(^{14}\)

S7  Electron Cooling Dynamics

In this work, the rise time ($\tau_r$) is the time required for the electron temperature ($\Delta T_e$) to rise from 10% to 90% of its maximum value. Similarly, the fall time ($\tau_f$) is the time required for $\Delta T_e$ to fall from 90% to 10% of its maximum value. To obtain a function $\Delta T_e(t)$ with $\tau_r = 100$ fs and $\tau_f = 4$ ps, we set $\tau_1 = 0.06$ ps and $\tau_2 = 1.8$ ps. Both $\tau_1$ and $\tau_2$ were obtained...
by iteration.

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