Supplemental Material

Modulated resonant transmission of graphene plasmons across a λ/50 plasmonic waveguide gap

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1. Electromagnetic Simulations

The electromagnetic response of the structure was numerically simulated using COMSOL Multiphysics – a commercial full-wave simulation software based on finite element method (FEM). The port boundary condition was applied to the entrance portion of the input MIM waveguide in order to launch the TM_0 mode and to make it transparent to the reflected TM_0 mode. The same boundary condition was applied to the exit portion of the output MIM waveguide without the mode excitation. The half space over the device was enclosed by perfectly matched layers (PMLs) to mimic the open boundaries for the unbound waves radiating from the waveguide gap. We adopted the triangular mesh, the size of which was chosen to range from 1 to 10 nm in the MIM waveguide region, from 0.2 to 5 nm in the waveguide gap region, and from 5 to 200 nm in the air region to ensure that the mesh size was sufficiently smaller than the spatial variation of the electromagnetic fields. This was confirmed by checking the simulation conversion, so that further mesh refinement had only a negligible effect on the resulting electromagnetic fields profile.

2. Optical Conductivity of Graphene

In our FEM simulations, graphene is modeled as a thin layer with a thickness of δ = 0.3 nm and possessing the relative permittivity $\epsilon_G = 1 + i\sigma/(\epsilon_0 \omega \delta)$. The complex optical conductivity of graphene $\sigma(\omega)$ is evaluated within the local random phase approximation [23]:

$$\sigma(\omega) = \frac{2ie^2T}{\pi\hbar(\omega + i\Gamma)} \log\left[2\cosh\left(\frac{E_F}{2T}\right)\right] + \frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right) + \frac{4i\omega}{\pi}\int_0^\infty d\eta \, \frac{H(\eta) - H\left(\frac{\omega}{2}\right)}{\omega^2 - 4\eta^2}\right],$$

where

$$H(\eta) = \frac{\sinh(\eta/T)}{\cosh(E_F/T) + \cosh(\eta/T)}.$$

The temperature T is set as 300 K, and the intraband scattering rate is $\Gamma = ev_F/\mu\sqrt{n\pi}$, where μ is the carrier mobility of graphene [20 in the main text]. Here we ignore the scattering by the optical phonons in graphene because our target frequency $\omega =$ 0.165eV is lower than the bottom of the graphene optical phonon band $\omega_{\mathrm{oph}} \sim$ 0.2eV [34], as explained in the Section 3 below. The dielectric functions of Au and SiO_2 are adopted from Palik [19].

3. Selection of the Operation Frequency Window

The operating frequency range of our devices is fundamentally limited by two kinds of phonons: the polar phonons in the SiO_2 substrate (having energy of ~ 0.133 eV [19]) and the intrinsic optical phonons in graphene (having energy of ~ 0.2 eV [20]). Figure S1 shows the real and the imaginary permittivity of SiO_2 as reported by Palik [19]. One finds that, although the main phonon peak is located around 0.13 eV, the real part of the permittivity is still negative up to 0.155 eV. Therefore, in order to guarantee a low plasmonic loss, the operation frequency should be above 0.16 eV. Regarding the graphene optical phonons, due to the thermal broadening of 0.026 eV at room temperature, the interaction between the graphene plasmons and optical phonons starts to manifest itself at around 0.175 eV. Therefore, the actual frequency window of low-loss operation is between 0.16 eV ($\lambda_0 \approx 7.75$ μm) and 0.175 eV ($\lambda_0 \approx 7.1$ μm). If the operational wavelength approaches either of the phonon modes, the device performance may deteriorate due to the phonon-induced damping. Therefore, we selected the operation frequency near the middle of the phonon-free energy band at 0.165 eV ($\lambda_0 \approx 7.5$ μm).

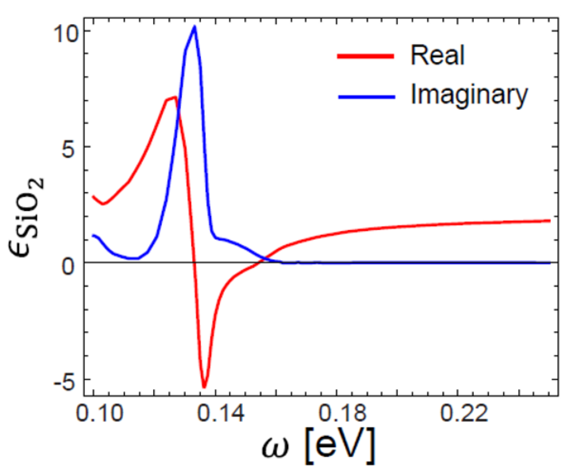

Fig. S1. Permittivity of SiO2 measured by Palik [19].

4. Condition for Graphene Plasmon Resonance

The graphene Fermi level $E_{\rm res}$ corresponds to a plasmonic resonance at which the denominator of the expression for t_G, $1 - r_{\rm GM}^2 \exp(2in_G k_0 L)$, is minimized, providing the maximum transmission. Then, the condition for the lowest order resonance is given by

$$\phi_{\rm GM}^r(E_{\rm res}) + {\rm Re}\{n_G(E_{res})\}k_0 L = 2\pi,$$

where $n_{\rm G}$ is the effective index and $\phi_{\rm GM}^r(E_{\rm res})$ is the reflection phase of graphene plasmon.

For $E_F \gg k_B T$ and $\omega \gg \gamma$, where γ is the scattering rate of electrons in graphene, the wavevector of the propagating graphene plasmon mode can be analytically expressed as [20]:

$$n_G k_0 = \frac{\pi \hbar^2 \omega^2 \epsilon_0 (1 + \epsilon_{\rm SiO2})}{e^2 E_F}.$$

However, the reflection phase, $\phi_{\rm GM}^r(E_{\rm res})$, is difficult to express analytically because the calculation involves boundary conditions with non-trivial geometry, and thus we calculate $\phi_{\rm GM}^r(E_{\rm res})$ numerically in this work.