Supplementary material for "Electrical Control of Optical Plasmon Resonance with Graphene"

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I. GATE-DEPENDENT DIELECTRIC CONSTANTS OF GRAPHENE

Gate-dependent complex dielectric constant of graphene is calculated from Eq. (1). $1/\tau$ can be set to zero because it has little effect on the dielectric constants at plasmon resonance energy E_R. Consequently, imaginary part of dielectric constant is dominated by interband transition (Fig. S1b). On the other hand, real part of dielectric constant has significant contribution also from intraband transition. Fig. S1a shows that intraband transition contributes monotonic decrease in the real part dielectric constant. Interband transition has a maximum at $2|E_F| = E_R$. This is because all optical transitions below E_R contribute a negative susceptibility, and transitions above E_R contribute a positive susceptibility to $\varepsilon_g^{'}(E_R)$.

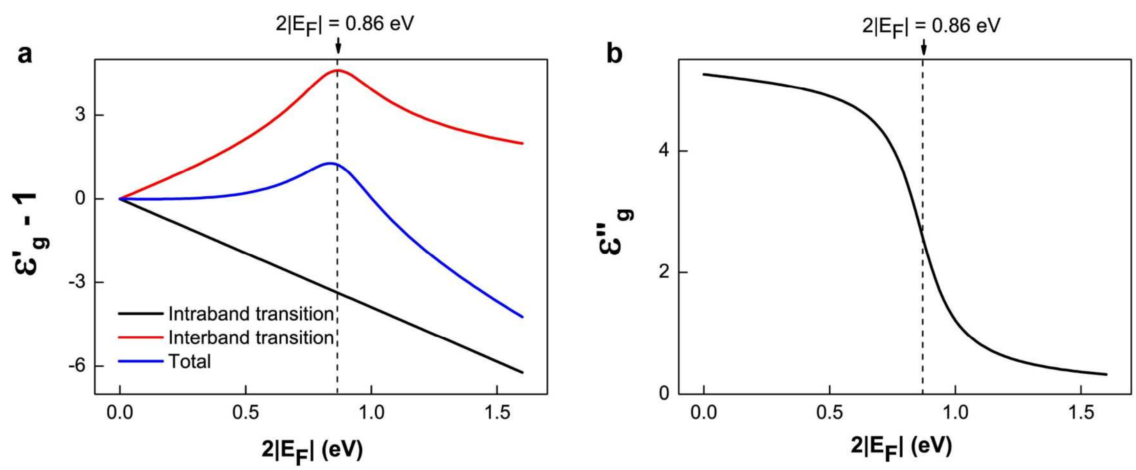

Figure S1. Gate-dependent dielectric constant of graphene. a. Real part. **b.** Imaginary part.

II. FINITE ELEMENT ANALYSIS ON OPTICAL PLASMON RESONANCE MODULATION WITH GRAPHENE

Numerical simulation (COMSOL Multiphysics) is performed to further verify our experimental results of plasmon resonance modulation with graphene. In the simulation, we set the diameter and length of gold nanorod to be 25 nm and 200 nm respectively (aspect ratio: 8). For the simplicity, the structure of the hybrid graphene-gold nanorod is modified so that nanorod is placed on top of graphene and glass substrate. Scattering cross-sections are calculated for two cases where graphene Fermi level is at 0 eV and 0.75 eV, corresponding to allowed- and blocked-interband transitions, respectively. Eq. (1) is used to obtain dielectric constants of graphene at each Fermi level. To facilitate the simulation, we assumed a thickness of graphene to be 1 nm. Because the susceptibility of graphene scales inversely with the thickness (Eq. (1)), the integrated response from graphene is independent of the thickness used as long as it is much smaller than other relevant dimensions. In Fig. S2a, simulation results show the plasmon resonance quality factor increases by 28% and resonance scattering intensity increases by 25%, which agrees well with the experimental data. Fig. S2b displays distribution of in-plane scattered electric field magnitude square on graphene surface. It shows dramatically enhanced electrical fields in hot spots at the two ends of gold nanorod. We find that the integrated in-plane light intensity within these two 20 nm x 20 nm hot spots on graphene constitutes 14% of total response integrated overall the whole horizontal plane of graphene.

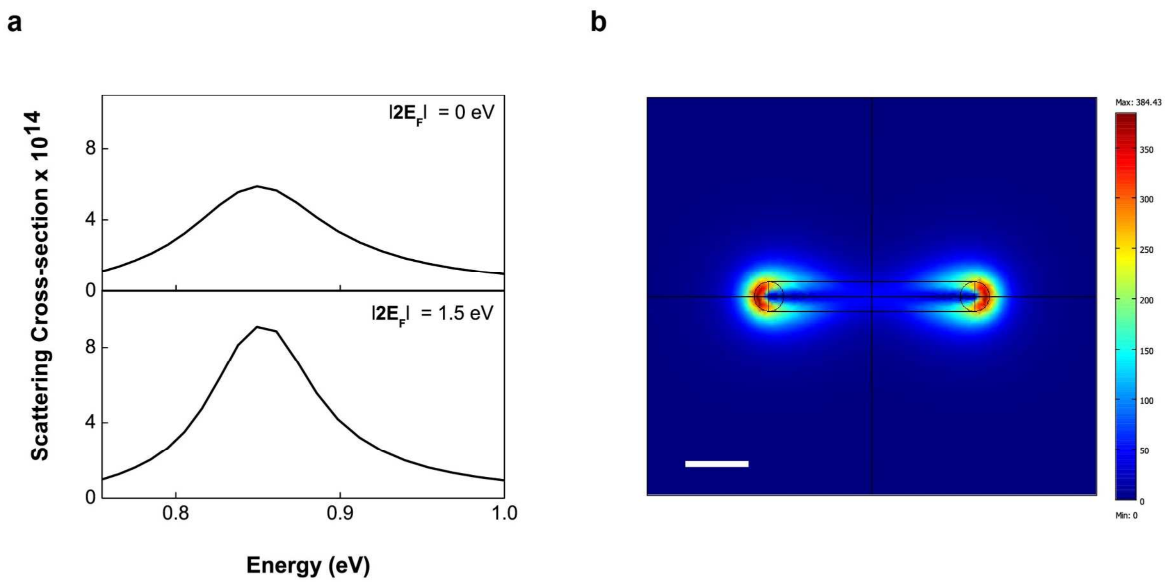

Figure S2. Numerical simulation results a. Scattering cross-section change due to the modulation with graphene by gating. Scattering cross-sections are normalized by plane wave incident light. **b.** Distribution of the in-plane scattered electric field magnitude square (V^2 / m^2) on graphene surface where fermi level is at 0.75 eV. White scale bar in the figure corresponds to 50 nm.

III. ESTIMATION OF SHOT-NOISE-LIMITED DETECTION SENSITIVITY

Shot-noise limited detection sensitivity for the scattered photons from hybrid graphene-nanorod structure is $\frac{\sqrt{N_{sct}}}{N_{sct}}$ where N_{sct} is the number of the scattered photons per second. In the experiment the power of the scattered light is measured as ~ 100nW with 1 mW laser excitation which is focused into ~ 1 um diameter spot on the sample in the backscattering configuration. Resonance scattering photon energy is 0.86 eV, and the corresponding number of photons per second is $7.26 * 10^{11}$ / sec. Therefore, shot-noise limited detection sensitivity is $1.17 * 10^{-6}$ / $\sqrt{Hz}$.