

《可调谐的声学型石墨烯等离子激元增强纳米红外光谱*》 的补充材料

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注释 1: 计算色散关系的方法

我们通过菲涅耳反射系数 $r_p(q, \omega)$ 方法计算 AGP 的色散关系. 计算的结构为石墨烯/空气间隙/金的多层结构, 如图 S3 所示.

该系统的 r_p 由以下方程决定:

$$r_p = r_g + r_m e^{i2k_a^z d} / 1 + r_g r_m e^{i2k_a^z d} \quad (S1a)$$

$$r_g = (\epsilon_{a\perp} k_g^z - \epsilon_{g\perp} k_a^z) / (\epsilon_{a\perp} k_g^z + \epsilon_{g\perp} k_a^z) \quad (S1b)$$

$$r_m = (-\epsilon_{a\perp} k_m^z - \epsilon_{g\perp} k_a^z) / (\epsilon_{a\perp} k_m^z + \epsilon_{g\perp} k_a^z) \quad (S1c)$$

下标“g”, “a”和“m”分别表示石墨烯、空气和金. d 代表单层石墨烯的厚度. r_g 和 r_m 分别代表石墨烯/空气和空气/金界面的反射率. $\epsilon_{g\perp}$ 和 $\epsilon_{a\perp}$ 分别代表石墨烯和空气的外平面介电函数. k_i^z 是沿 z 轴传播波的动量分量:

$$k_i^z = \sqrt{\epsilon_{i\perp} (\omega/c)^2 - [(\epsilon_{i\perp} / \epsilon_{i\parallel}) \cdot q^2]} \quad (S1d)$$

其中 $i = g, a$ 和 m , ω 是入射光的频率, c 是真空中光速. $\epsilon_{i\perp}$ 和 $\epsilon_{i\parallel}$ 分别表示相应 i 材料的面外和面内介电函数.

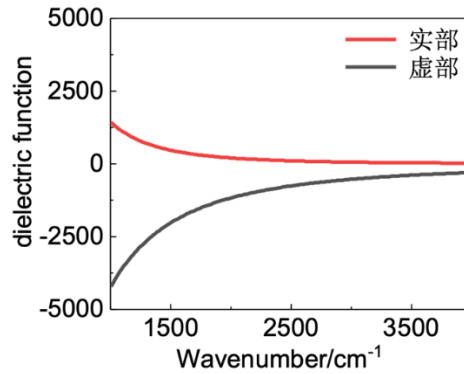


图 S1 金的介电函数

Fig.S1. Dielectric function of gold.

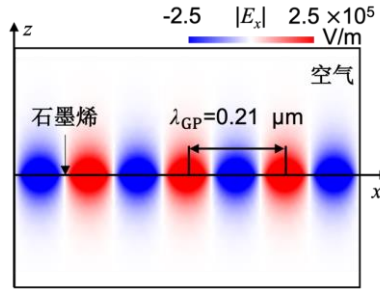


图 S2 石墨烯等离激元 (graphene plasmon, GP) 沿 x 轴的的电场强度分布图 (E_x). GP 的共振频率为 1600 cm^{-1}

Fig.S2. Electric-field distribution of graphene plasmon (GP) in Graphene at a resonance frequency of 1600 cm^{-1} .



图 S3 单层石墨烯/空气间隙/金多层结构的侧视图

Fig.S3. Side view of the layered structure of single-layer graphene/ airgap/ Au.

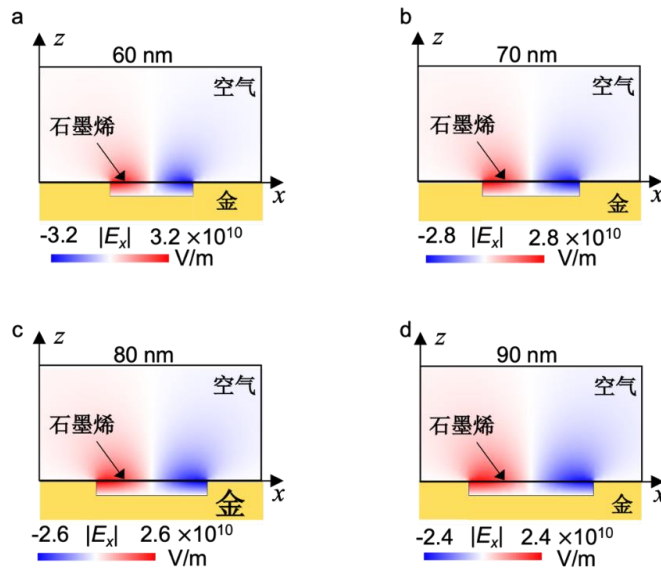


图 S4 基于不同金纳米腔室宽度的声学型石墨烯等离激元 (nanocavity-Acoustic graphene plasmon, n-AGP) 沿 x 轴的电场分布图 (E_x). 当金纳米腔室宽度为 60 nm (a), 70 nm (b), 80 nm (c), 90 nm (d) 时, n-AGP 沿 x 轴的 E_x

Fig.S4. Electric-field distribution (E_x) along the x -axis of nanocavity-Acoustic graphene plasmon (n-AGP) based on different gold nanocavity widths. When the width of the gold nanocavity is 60 nm (a), 70 nm (b), 80 nm (c), and 90 nm (d), E_x of nanocavity-Acoustic graphene plasmon (n-AGP).

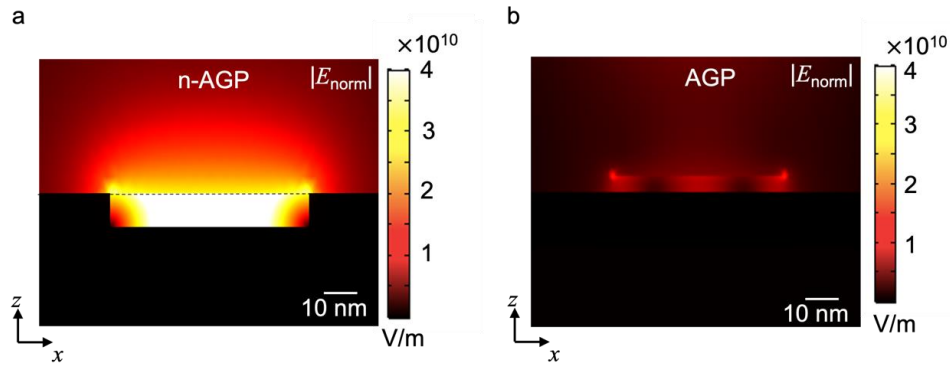


图 S5 n-AGP 和声学型石墨烯等离激元 (acoustic graphene plasmon, AGP) 的电场强度分布图. (a) n-AGP 的电场强度分布图 ($|E_{\text{norm}}|$); (b) AGP 的电场强度分布图 ($|E_{\text{norm}}|$). 石墨烯宽度为 60 nm, 石墨烯与金之间存在 10 nm 空气间隔. $E_{\text{norm}} = \sqrt{E_x^2 + E_z^2}$

Fig.S5. Electric-field distribution of n-AGP and acoustic graphene plasmon (AGP). (a) Electric-field distribution diagram of n-AGP ($|E_{\text{norm}}|$); (b) Electric-field distribution diagram of AGP ($|E_{\text{norm}}|$). Graphene has a width of 60 nm, and there is a 10 nm air gap between graphene and gold. $E_{\text{norm}} = \sqrt{E_x^2 + E_z^2}$.

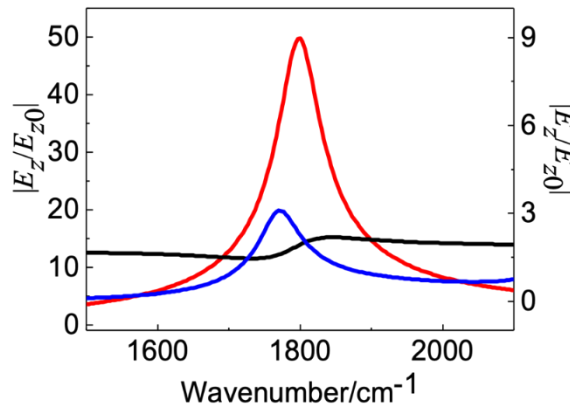


图 S6 不同石墨烯等离激元模式的归一化电场强度谱. 从石墨烯下方 5 nm 处提取归一化电场强度谱. 共振频率为 1800 cm^{-1} 时, n-AGP 的最高电场增强倍数 ($|E_z/E_{z0}|$) 约为 50 (红色曲线). 共振频率为 1770 cm^{-1} 时, GP 的最高电场增强倍数 $|E_z/E_{z0}|$ 约为 3. (蓝色曲线) 共振频率为 1843 cm^{-1} 时, AGP 的最高电场增强倍数 $|E_z/E_{z0}|$ 约为 2 (黑色曲线). E_{z0} 为仅电偶极子存在时的电场强度

Fig.S6. Normalized electric-field spectra of different graphene plasmon modes. Normalized electric-field spectra from 5 nm below the graphene. The maximum electric field enhancement factor ($|E_z/E_{z0}|$) of the n-AGP is approximately 50 at a resonance frequency of 1800 cm^{-1} (red curve). For the GP, the maximum electric field enhancement factor $|E_z/E_{z0}|$ is about 3 at a resonance frequency of 1770 cm^{-1} (blue curve). The maximum electric field enhancement factor $|E_z/E_{z0}|$ of the AGP is approximately 2 at a resonance frequency of 1843 cm^{-1} (black curve). E_{z0} is the electric field intensity when the electric dipole is directly excited.

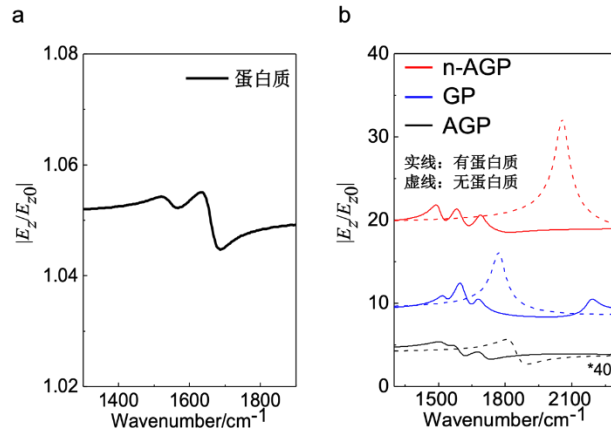


图 S7 蛋白质分子对不同石墨烯等离激元模式归一化电场强度谱的影响 (a) 宽度为 60 nm，高度为 10 nm 的蛋白质的归一化电场强度谱， E_{z0} 为仅电偶极子存在时的电场强度；(b) 有（实线）无（虚线）蛋白质时，不同石墨烯等离激元模式的归一化电场强度谱的比较

Fig.S7. Effect of protein molecules on the normalized electric-field spectra of different graphene plasmon modes: (a) Normalized electric-field spectra of protein with a width of 30 nm and a height of 10 nm, E_{z0} is the electric field intensity when the electric dipole is directly excited; (b) comparison of normalized electric-field spectra of different graphene plasmon modes with (solid line) and without (dashed line) proteins.

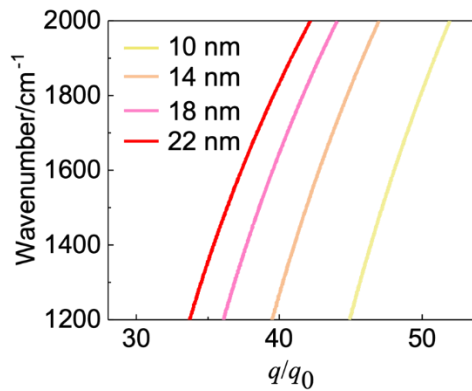


图 S8 石墨烯与金相距不同距离时 (10 nm, 14 nm, 18 nm, 22 nm)，计算 AGP 的色散关系
Fig.S8. Dispersion of AGP at at different distances (10 nm, 14 nm, 18 nm, 22 nm) between graphene and gold.