Supplementary Material

Title: Sharp phase variations from the plasmon mode causing the Rabi-analogue splitting

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1. Sharp variations of the reflection phase

The underlying reason about the sharp variations of the reflection phase can be explained by the microscopic model. When the incident light impinges the metallic nanohole, a part of light is directly reflected by the metal surface with the amplitude of A, and a part of light is coupled to the plasmon mode with the amplitude of B. The coupled plasmon mode on the metal surface can be scattered to the free space by the nearby nanoholes. As a result, the reflection light of the nanohole array has two contributions (the directly reflected light and the scattered plasmon mode), and its electric field is determined by

$$\begin{aligned} E &= A\cdot\exp(i\varphi) + B\eta\exp[i(\frac{2\pi}{\lambda}n_{\text{eff}}\,p+\beta+\beta')] \\ &+B\eta\tau\exp[i(\frac{4\pi}{\lambda}n_{\text{eff}}\,p+\beta+\beta')]+\dots \\ &+B\eta\tau^{m-1}\exp[i(\frac{2m\pi}{\lambda}n_{\text{eff}}\,p+\beta+\beta')]. \end{aligned} \tag{1}$$

Here, φ is the phase shift of the directly reflected light. η denotes the scattering efficiency of the nanohole (from the plasmon mode to the free-space light). $n_{\text{eff}} = n_{\text{eff}}^{\text{r}} + i\times n_{\text{eff}}^{\text{i}}$ is the effective refractive index of the plasmon mode. β is the phase shift of the coupling process from the free-space light to the plasmon mode. β' is the phase shift of the scattering process from the plasmon mode to the free-space light. $\tau=|\tau|\exp(i\delta)$ represents the transmittance coefficient of the SPP mode [1]. In order to simplify the expression, $\Gamma=|\tau|\exp(-2\pi n_{\text{eff}}^{\text{i}}p/\lambda)$, $C=B\eta\exp(-2\pi n_{\text{eff}}^{\text{i}}p/\lambda)$, and $\alpha=2\pi n_{\text{eff}}^{\text{r}}p/\lambda+\delta$ are introduced. Hence, Eq. (1) can be written as

$$E = A\cdot\exp(i\varphi) + \frac{C\left\{\exp[i(2\pi n_{\text{eff}}\,p/\lambda+\beta+\beta')]-\Gamma\exp[i(\beta+\beta'-\delta)]\right\}}{1+\Gamma^2-2\Gamma\cos(\alpha)}. \tag{2}$$

From Ref. [1], we can obtain $\Gamma\approx0.93$. The simulation shows that the reflection phase of a gold film at the investigated wavelength range (700-800 nm) is about $\varphi\approx-0.86\pi$. Based on the destructive interference at the resonant wavelength, it can be concluded that the $\beta+\beta'\approx0.21\pi$, $\delta\approx0.0696\pi$, and $A\approx14.28C$. The calculated reflection ($|E|^2$) and the reflection phase [arctan(Im(E)/Re(E))] based on Eq. (2) are depicted in Figure S1(a)(b), which according well with the simulated results in Figure 2(d)(e). This coincidence verifies the validity of the microscopic model. The intensities and phases of the directly reflected light [first part in Eq. (2)] and the scattered plasmon mode [second parts in Eq. (2)] are also plotted in Figure R1(c)(d). It is observed that the intensity of the scattered plamon mode reaches the maximum at the resonant wavelength. Moreover, the phase of the scattered plamon mode decreases with the wavelength, which results in the decrease of the reflection phase with the wavelength. Based on Eq. (2), the sharp change of the reflection phase stems from the interference of the directly reflected light and scattered plasmon mode, of which both the amplitudes and phases can influence the reflection phase.

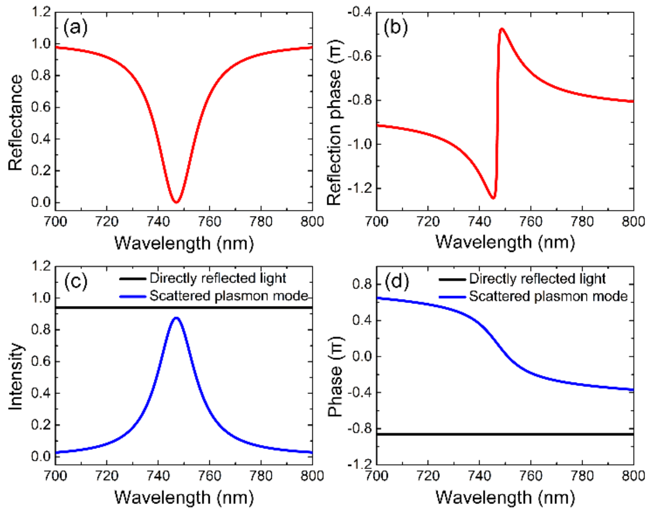

Figure S1: (a) Reflectance ($|E|^2$) and (b) reflection phase [arctan(Im(E)/Re(E))] calculated based on Eq. (2) at different wavelengths. (c) Intensities and (d) phases of the directly reflected light and the scattered plasmon mode . The black lines denote the directly reflected light, and the blue lines denote the scattered plasmon mode on the metallic nanohole array.

Reference:

[1] Liu H, Lalanne P. Microscopic theory of the extraordinary optical transmission. Nature 2008, **452**, 728-31.