Extraordinary Optical Transmission in Nanopatterned Ultrathin Metal Film without Holes

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Supplementary Information

I. Period and R/a Variation
II. Transverse Electric Field Profile
III. Convergence with Number of Bloch Waves
I. PERIOD AND R/a VARIATION

Period Variation: We present the simulation results for different periods \((a) = 650\,\text{nm}, 700\,\text{nm}\) and \(750\,\text{nm}\) for constant \(R/a = 0.33\) in Fig. S1. It can be seen that the surface plasmon resonance peak of gold appears at same wavelength \(\lambda_{sp} \sim 504\,\text{nm}\) for all the three cases. The EOT peak appears at a wavelength slightly smaller than \(a\). Notably, the position of the transmission peak scales with the period of the structure, that is, the peak transmission wavelength increases as \(a\) increases. The Wood’s anomaly where \(T = 0\) is also seen at \(\lambda_W = \sqrt{3a}/2 \sim 580\,\text{nm}, 610\,\text{nm}\) and \(650\,\text{nm}\) for \(a = 650\,\text{nm}, 700\,\text{nm}\) and \(750\,\text{nm}\), respectively. Corresponding to \(a = 650\,\text{nm}, 700\,\text{nm}\) and \(750\,\text{nm}\), the EOT peak appears at wavelength \(\lambda_1 \sim 625\sim 640\,\text{nm}, 665\sim 695\,\text{nm}\) and \(707\sim 720\,\text{nm}\), respectively. For our analysis, we choose \(a = 750\,\text{nm}\) since it is closest to the experimental structure. The precise shape of the transmission curves does not scale with \(a\) since the dielectric function of gold is wavelength-dependent.

![Figure S1. Simulated total transmission and specular transmission spectra for the nanocup structure with different periods \((a) = 650\,\text{nm}, 700\,\text{nm}, \text{and} 750\,\text{nm}.\) The value of \(R/a = 0.33\) for all the cases.](image)
**R/a Variation:** We present the simulation results for different \( R/a = 0.27, 0.30, \) and 0.33 for constant pitch \( a = 750 \text{ nm} \) in Fig. S2. Similar to Fig. S1, the surface plasmon resonance peak of gold appears at same wavelength \( \lambda_{sp} \approx 504 \text{ nm} \) for all three cases. Since the period is constant for all the cases, the EOT peak (~700 nm) and the Wood’s anomaly point (~650 nm) appear at nearly the same wavelength. Notably, when \( R/a \) is decreased the EOT peak becomes narrower and the transmission intensity also reduces due to the decrease in aperture of the nanocup. We present the results in the manuscript for \( R/a = 0.33 \), which corresponds to the experimental structure.

![Simulated total and specular transmission spectra for the nanocup structure with different R/a values](image)

**Figure S2.** Simulated total and specular transmission spectra for the nanocup structure with different \( R/a = 0.27, 0.30, \) and 0.33. The value of period \( (a) = 750 \text{ nm} \) for all the cases.
II. TRANSVERSE ELECTRIC FIELD PROFILE

The electric field intensity $|E|^2$ at the EOT wavelength $\lambda_1 \sim 700$ nm in the x-y plane (Fig. S3) just below the surface of the nanocup shows an intensity distribution complementary to that in the xz-plane (Fig. 6a). The results are shown for incident field with $x$ polarization. The $|E|^2$ has peaks in small regions at the edges of the circular aperture where $|E|^2$ is enhanced by ~50-60 in both the xy and xz cross-sections. Dipolar charge distributions are formed at the edges of the nanocup. This is typical of surface plasmon propagation along the $x$-axis (ref. 26). There are a pair of additional sub-peaks on either side of the center of the nanocup surface (Fig. S3 and Fig. 6a), where the $|E|^2$ is enhanced by ~50. There is a node of the electric field at the center of the nanocup surface as seen in both Fig. S3 and Fig. 6a. Since the nanocup geometry can be envisaged as a combination of many holes of decreasing radii, we used five layers of holes with decreasing radii ($R, 0.8R, \ldots, 0.2R$) to model the nanocup field intensity. We can see that the electric field plot in Fig. S3 is actually the superposition of well-known field intensity from a single hole (ref. 26) with field maxima lying along $x$-axis for incident field with $x$ polarization.

III. CONVERGENCE WITH NUMBER OF BLOCH WAVES

We have investigated the convergence of the transmission with increased number of Bloch waves ($N_G$) per polarization as summarized in Fig. S4, using a 5 nm thick gold layer at the bottom of the nanocup corresponding to the geometry used for simulation in Fig. 4a. The scattering matrix has dimension of $2N_G \times 2N_G$. The $N_G$ values correspond to closed shells of
reciprocal lattice $G$ vectors. The convergence of short wavelengths ($\lambda < 660$ nm = Woods anomaly wavelength, $\lambda_w$) or at longer wavelengths $\lambda > 800$ nm is very good for all the chosen $N_G$ values. In the EOT region 650-850 nm (Fig. S4), the transmission is more sensitive to the number of Bloch waves, and we find $N_G = 535, 769$ are converged. Both $N_G = 535$ and $N_G = 769$ show two EOT peaks with a narrower feature around 700 nm and a broader feature (consisting of multiple peaks at 720-780 nm). These two features combine to produce the broader experimental peak centered around 704 nm.

Figure S4. Simulated transmission spectra with $N_G = 397, 535, 613, 769$ compared to the experimental transmission.