**Strong Field Concentration at the Subwavelength Scale by a Metallic Hole-Array Structure**

CNF Project # 1491-06
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Abstract:
A series of metallic, two-dimensional hole-array (2DHA) samples is fabricated and their transmission properties measured at mid-infrared wavelengths (1.5-20 µm). At plasmonic resonance, the 2DHA sample exhibits a normal incidence transmittance of 80% at \( \lambda = 7.6 \) µm. Given that the air-hole filling fraction (F.F.) of the sample is 25%, the transmission flux through the 2DHA sample is calculated to be 320%, which indicates a large electric field enhancement in the vicinity of the 2D holes. This exceedingly large enhancement is attributed to the strong coupling between incident photons and surface-plasmonic modes.

Summary of Research:
There has been a considerable interest in metallic, two-dimensional hole-array (2DHA) structures for the past decade. The interest was triggered by the first experimental result reported by Ebbesen et al [1], in which significantly enhanced transmission through metallic holes was observed at a wavelength much larger than the diameter of holes (\( \lambda >> d \)). This observation led to the suggestion of several interesting applications of the 2DHA in subwavelength optics and near-field microscopy. To date, most previous experiments of the 2DHA were performed at either visible or near-infrared (NIR) wavelengths.

All of this experimental data seems to suggest a fundamental trade-off between the highest achievable transmittance through the 2D holes and their corresponding (\( \lambda/d \)) value. Here, we successfully extend the operating wavelength of the 2DHA to the mid-infrared wavelengths (\( \lambda = 5-10 \) µm). More importantly, we achieve a > 300% electromagnetic (EM) field enhancement through the 2D holes while maintaining an exceedingly high transmittance of up to 80% at a deep sub-\( \lambda \).

Our 2DHA samples are fabricated on silicon (Si) substrates using a combination of standard optical lithography and metal lift-off process. Figure 1 shows a large area scanning electron microscopy (SEM) image of the fabricated Au-2DHA sample. The samples have an area of 5 mm × 5 mm, a hexagonal lattice geometry, a lattice constant \( a = 2.5-3.72 \) µm, and a hole diameter \( d = 1.3 \) µm. The thickness of Au film is 50 nm. The optical properties of the fabricated sample were characterized using Fourier transform infrared (FTIR) spectroscopy over the spectral range \( \lambda = 1.5-20 \) µm. To obtain the absolute transmittance \( T \) of the 2DHA, the transmission spectra taken from the 2DHA samples are normalized to that of a bare Si wafer.

Figure 1: A SEM image of 2DHA samples. The lattice constant is \( a = 2.5-3.72 \) µm, the diameter of holes \( d = 1.3 \) µm, and the thickness of Au film \( t = 50 \) nm. Scale bar: 2 µm.
In Figure 2, we show the measured transmission spectra taken from a series of 2DHA samples, having the same $d = 1.3 \, \mu m$ and $t = 50 \, \text{nm}$ but five different $a = 2.5, 2.728, 2.976, 3.224,$ and $3.72 \, \mu m$, respectively.

For all of the samples, we observed pronounced transmission peaks and minima at the infrared, $\lambda \sim 7-10 \, \mu m$. Furthermore, the peak transmission is shifted to a longer $\lambda$ for samples with a larger lattice constant. There is also a linear dependence between the peak-$\lambda$ and $a$. For the $a = 2.5 \, \mu m$ sample, a peak transmittance of $T = 80\%$ is observed at $\lambda = 7.6 \, \mu m$, or equivalently, $\lambda/d = 5.8$.

Given that the hole F.F. of the sample is 25%, the transmission flux is calculated to be 320%, which indicates a large electric field enhancement inside and near the 2D holes.

This experimental data, to our best knowledge, represent the first experimental demonstration of an exceedingly high transmission through a 2DHA structure at the deep sub-$\lambda$ regime.

In summary, 2DHA samples are fabricated using a thin Au of 50 nm. Experimental transmission spectra exhibit a strong field concentration at a deep subwavelength ($d/\lambda \sim 1/6$) in the mid-infrared wavelength ($\lambda \sim 7-10 \, \mu m$).

References: