Student Paper

Particle-In-Cell Simulation of Resonant-Cavity-Enhanced Extraordinary Transmission through Sub-wavelength Plasmonic Structure

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Imaging of objects smaller than half a wavelength is impeded by the diffraction limit for sub-wavelength apertures. Recent progresses in nano-material and MEMS processing technologies enable us to create micro/nano structures on materials such as metal and semiconductor. It has been demonstrated [1] and modeled [2] that by taking advantage of surface plasmons that flow along the apertures, higher than expected transmissions at wavelengths longer than diffraction limit can be achieved which yield the promise of improved resolution.

For plasmonic material with apertures/periodic gratings (Fig. 1), it is possible to support resonant-cavity mode along the aperture slot. For this mode, the field decays exponentially away from the normal of the dielectric-metal interface (along y-direction). This is a slow wave mode due to the involvement of surface plasmon. Peak transmission occurs at frequencies that can be supported by forming standing waves inside the aperture along the x-direction. We term this kind of transmission as resonant-cavity enhanced transmission. The operating principle is close to cavity-mode-based antenna, such as aperture or patch antenna. The difference is that the bounding metallic material supports surface plasmon along the dielectric-metal interface. The subluminal resonant mode supported by the structure enables the possibility of transmitting at wavelengths longer than that bounded by the diffraction limit.

We have modeled extraordinary transmissions through periodic grating with sub-wavelength apertures in a two-dimensional particle-in-cell (PIC) code. Unlike previous modeling work [2], using a particle code, the plasmon is modeled as an ensemble of particles and it enables us to have a kinetic-level view of the interaction between incident wave and collective motion of surface plasmons. Figure 1a shows the modeled plasmonic structure with sub-wavelength periodic gratings. In the simulation, the plasmonic slab is modeled by placing electrons in two metal blocks and the background ions are treated as stationary. This will naturally produce collective plasmonic oscillation in the simulation. The simulated structure has aperture width (2a) = 90nm, periodic grating length (2d) =1710 nm, and grating thickness (h) =1800 nm. The simulation domain has 400×200 grids with grid spacing = 7, 9 nm along x, y direction, respectively. In each grid, we placed 5 particles, totaling ~220,000 particles. These particles are weighted to match the density of Silver. The simulation time step is chosen to be smaller than Courant's condition. Periodic boundary conditions are applied along y direction.

To study the resonant transmission, a broad-band Gaussian pulse TM wave was launched from the left and interacted with the plasmonic structure. The half-maximum bandwidth of the Gaussian pulse is ω_p (plasma frequency, $\omega_p = 13673$ THz, for silver in our simulation). On the right side, we placed a monitoring point. The incident and transmitted signal in time-domain are collected and a Fourier transformation has been applied. The ratio between transmitted and incident wave are plotted in Figure 1b. As we can see that there are five peaks in the transmitted spectrum with decreasing amplitude at higher frequencies. These peaks correspond to resonant cavity-modes. It can be seen from Fig. 2a that transmission at wavelengths much longer than the aperture width has been generated. The ratio between transmission wavelength and aperture width (2a) can be as high as ~ 60. This is much larger them the diffraction limit ~1.

Furthermore, PIC simulations are performed by launching sinusoidal plane wave at frequencies of these resonant peaks determined from Figure 1b. To excite resonant cavity mode, standing wave of magnetic field perturbation along x direction needs to be formed along the slot. Snap-shots of magnetic field distribution near the aperture at selected incident frequencies are shown in Figure 2. It is also found that first three resonant frequencies scale nearly linearly with

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grating thickness (see Figure 1c). This further confirms that standing waves were trapped inside the aperture. Figure 3 shows electron velocity oscillations Vy inside the plamonic material along the slot. This indicates that the standing wave couples to the plasmon oscillation along the surface of the metal.

References

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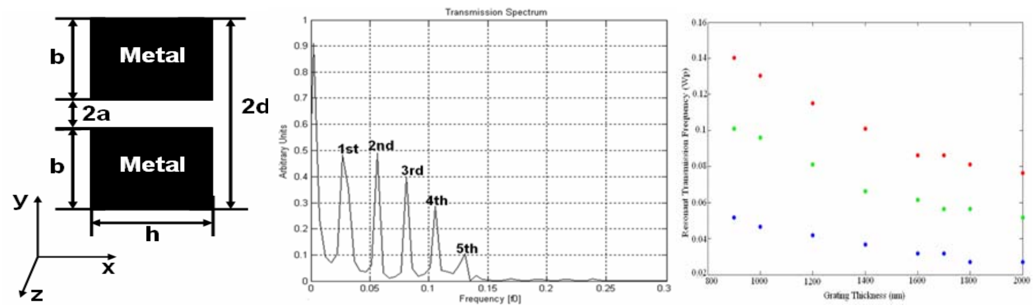


(a) (b) (c)

Figure 1: (a) Geometry of the modeled plasmonic structure with sub-wavelength periodic grating. **(b)** Spectrum of extraordinary transmission through the aperture array, the frequency has been normalized to plasma frequency. Five frequency peaks correspond to five resonant transmission modes. **(c)** First three resonant frequencies scale nearly linearly with grating thickness.

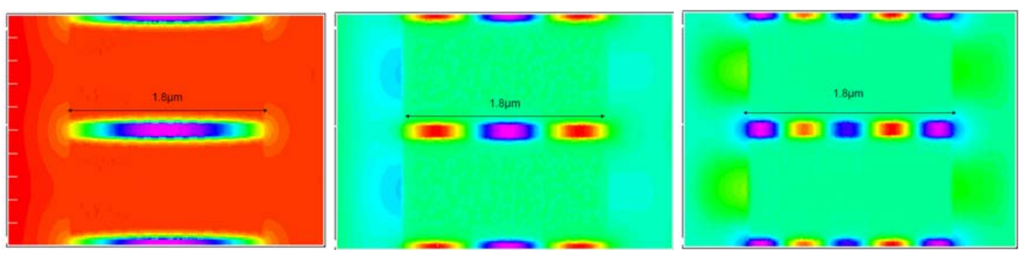
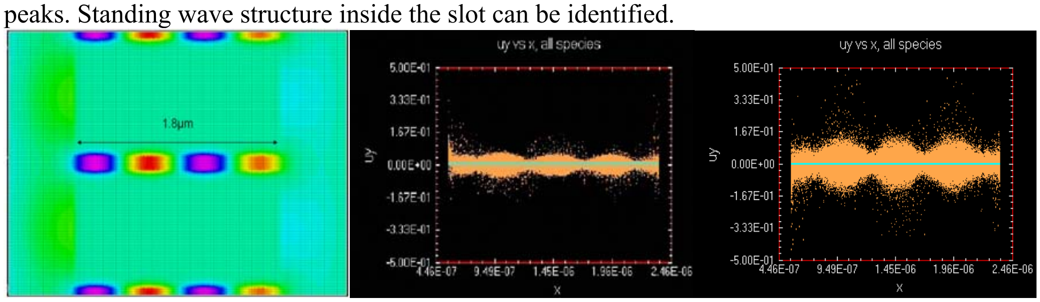


Figure 2: Magnetic field Bz distribution (red: high; blue/pink: low) obtained from simulation for the structure excited with frequencies corresponding to 1st, 3rd and 5th resonant transmission peaks. Standing wave structure inside the slot can be identified.



(a) (b) (c)

Figure 3: (a) Magnetic field Bz distribution for the structure excited by the frequency corresponding to the 4th resonant transmission peak. (b, c) Snap-shot of distributions of particle velocity Vy inside the metal the along the slot. Panels b,c correspond to different instants. Vy is oriented along the direction of electric field of TM mode EM wave.