Enhanced Light Transmission Through a Nanoscale Metallic Aperture by Surface Waves : a FDTD Study

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Introduction

Circular holes with diameter (d) smaller than the wavelength (λ) of incident radiation are conventionally considered to possess poor transmissive properties with the transmission normalized to the area of the hole being proportional to $(d/\lambda)^4$ [1]. The recent discovery of the enhanced light transmission through subwavelength holes arrays has sparked a keen interest in the fields of plasmonics, near-field optics and optics of metals [2]. The high spatial resolution and surface-guided character of the surface evanescent field (surface plasmons) is of utmost interest for applications in optical storage, biophotonics, lithography, near-field optical microscopy and integrated photonic circuits.

Aim

- The Finite-Difference Time-Domain (**FDTD**) method combined with the Lorentz-Drude (**LD**) model for dispersive media allows the full and accurate electromagnetic (EM) analysis of structures of arbitrary shape and composition.
- The sub-λ metallic nanoaperture surrounded by grooves is studied by FDTD to investigate the physical mechanisms driving the phenomenon of extraordinary transmission.

Method

FDTD:

- Numerical solution to Maxwell's equations without approximations
- Time-domain: enable to directly observe temporal evolution
- Scaling property: allows EM simulation over the full spectral range and to model structures with unit cell dimension $\Delta x \leq \lambda/10$

Lorentz-Drude model:

- Implementation of the LD model in FDTD enable to accurately simulate the dielectric function of dispersive materials like metals and biochemical components : Ag, Al, Au, Ni, H_2O, human cells…

$$\varepsilon(\omega) = \varepsilon_{r,\infty} + \sum_{k=0}^{K} \frac{f_k \omega_p^2}{\omega_k^2 - \omega^2 + j\omega\Gamma_k}$$

FDTD is applied to the analysis of an aperture in a thin metal film:

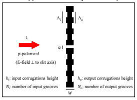

Fig. 1 Structure model. The material is silver (Ag)

Results

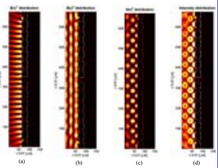

Fig. 2 Field distribution with λ=500nm, a=250nm, N_i=N_o=6, Λ_i=Λ_o=500nm, W=300nm, h_i=70nm, h_o=50nm. The E_x-field pattern distribution (2a) in the illuminated side is created by the interference of evanescent surface waves which enhance the near-field intensity. The field intensity distribution (2d) shows a regular array of phase singularities whose locations relative to the slit were found to be linked with the coupling of incident light with the slit waveguide mode [4].

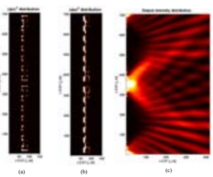

Fig. 3 Surface currents (3a-b) generated by the incident electric fields travel along the slit walls and transfer energy to the output side of the plate. This energy is then reradiated into a free-propagating EM wave to enhance the measured transmittance. Proper patterning of the output metallic surface allows the transmitted light to be focused in the near-field or far-field. Fig. 3c shows the near-field output intensity distribution without optimization of the output surface.

Factors controlling the slit transmittance:

- Slit waveguide mode (no cutoff for p-polarized light)
- Constructive interference of surface waves (surface plasmons) with the directly incident light on the slit increases coupling with the waveguide mode
- Transport of EM energy inside the sub-λ aperture by surface currents and re-radiation by surface charges

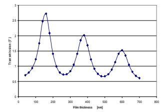

Fig. 4 Transmission as a function of film thickness W for a bare slit (N_i=N_o=0, a=40nm). The slit supports a guided-mode for p-polarized light with partial reflection at the open ends which is responsible for the Fabry-Perot dependence of the transmittance with slit thickness.

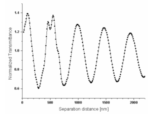

Fig. 5 Normalized transmittance as a function of single groove-slit separation distance. The surface wave generated at the groove interferes with the directly incident wave on the slit to produce the strongly periodic dependence.

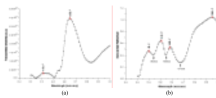

Fig. 6 One notable benefit of FDTD is the ability to directly measure the reflected component. There is a good overall correlation between transmission peaks (6a) and zero-order reflection minima (6b). Same structure as Fig.2 but with N_i=N_o=1 and h_o=0.

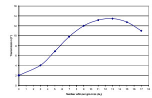

Fig. 7 The grooves enhance the near-field intensity around the slit. For a given fixed wavelength and structure geometry, transmission increases with the number of input grooves until reaching a peak value from which it monotonically decreases.

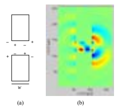

Fig. 8 The surface currents produce an accumulation of oscillating surface charges at the corners of the slit which emulate a radiating electric dipole at both ends. This is represented schematically (8a) and by a FDTD screenshot of the E_x-field (8b). In this example (λ=W=500nm, a=λ/2), the input and output dipoles are oppositely charged: π phase difference.

Conclusion

The metallic nanoaperture has numerous potential applications among others in lithography, optical data storage and light-emitting diode. The interaction between light and a subwavelength metallic aperture surrounded by grooves is a complex EM problem. The FDTD numerical method is used to investigate the mechanisms behind the phenomenon of enhanced transmission through a sub-λ metallic aperture. It is found that the transmittance is governed by three main factors: slit waveguide mode, interference of surface waves and transport of energy via surface currents.

We are now investigating the dynamical processes and conditions leading to constructive interference of the surface waves. In the future, the analysis will be extended to structures with axial symmetry of revolution and to the optimization of the geometrical parameters.

References

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