Electromagnetic Propagation Through Subwavelength Hole or Slit Arrays in Thick Metal Layer Covered with Dielectric Nanofilm

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Abstract — We considered electromagnetic propagation through subwavelength-dimensioned nanohole arrays as well as through subwavelength slits in optically thick metal screens. Surface plasmon resonance enables extraordinarily high optical transmission through such structures. We analyzed the field distribution tuning by a nanometric dielectric layer deposited over the structure surface. Such films may be formed e.g. through adsorption of particles from the environment. We used finite element method for modeling of our structures. The near field distribution around the subwavelength holes and slits is changed, thus offering a possibility for practical application of extraordinary transmission structures in e.g. electromagnetic/optical sensing and telemetry.

Keywords — Electromagnetic Propagation, Extraordinary Optical Transmission, Nanoplasmonics, Subwavelength Hole Arrays.

I. INTRODUCTION

Since Ebessen and coworkers discovered a few years ago the effect of extraordinary optical transmission through subwavelength apertures in optically thick metal films [1], a large interest arose for it and a number of treatises was published on that topic [2]-[6]. Several basic geometries were considered theoretically and experimentally, including ordered and disordered arrays of subwavelength nanoholes (the holes themselves having various shapes and dimensions), single subwavelength apertures surrounded by concentric annular corrugations and various kinds of 2D slits and troughs.

If an optically thick metal film with an array of holes is illuminated by electromagnetic radiation with a wavelength much larger than the hole diameter, according to the conventional Bethe-Bowcamp theory [7], [8] no radiation should be transmitted at all. However, under certain condition an extraordinarily large portion of the incident radiation is transmitted instead. The phenomenon is contributed to the surface plasmon polaritons (SPP) appearing on the surface of the metal film. The SPP are excited by the impinging electromagnetic wave if their wavelengths coincide. Along the propagation direction the SPP are evanescent, i.e. they decay exponentially both toward the substrate and toward the surrounding fluid.

The extraordinary optical transmittance through subwavelength holes is of large practical importance for different nanophotonic applications. The strong localization of the fields within the holes, which may exceed several orders of magnitude, appears especially important, since it could be used for the practical implementation of nonlinear optical effects which require exceedingly strong fields, and ultimately for the fabrication of all-optical active devices [9], [10].

Plasmonic surfaces generally, when situated in real environments, experience adsorption of particles from the surrounding fluid (gas or liquid) which, as a consequence, form a thin dielectric sheet (with a thickness which may range from below 1 nm to even a few hundred of nm). Since in plasmonic structures electromagnetic fields are by definition located on the structure surface and are strongly evanescent elsewhere, these tiny adsorbed dielectric sheets change the refractive index exactly in the place where its influence is largest. Thus the overall electromagnetic properties of the structure may be strongly affected and the performance changed. Furthermore, practically all surface plasmon resonance sensor utilize just this in order to operate and their performance is tuned by the adsorbed layer enabling detection of minuscule amounts of analytes [11].

In this paper we analyze the influence of the dielectric adlayers to the performance of arrays of subwavelength holes or slits. Such structures have been proposed previously for plasmon sensing application and are of large practical interest. We utilize full finite element modeling to analyze electromagnetic propagation through a subwavelength nanohole array for two different geometries, for a single hole surrounded by annular corrugations and for metal film with slits narrower than the operating wavelength. We consider both the case of free metal surfaces and the case when a thin (1-10 nm) dielectric film is deposited over the metal surface.
II. THEORY

In a general case, the shape, dimensions, number and spatial layout of the nanoholes can be arbitrary. The structure is illuminated by a normally impinging plane electromagnetic wave. The metal film it thick enough to serve as an opaque screen, and the holes are much smaller than the operating wavelength. In our case an array of concentric annular grooves exists on the surface. Both holes and corrugations serve as a modulation to the metallic film surface, since an electromagnetic wave cannot excite SPP on a perfectly smooth and flat surface.

When an electromagnetic wave arrives, it combines with electrons into a SPP; the SPP are transmitted through the holes. A surface corrugation of some kind is necessary for the coupling between propagating modes and in-plane plasmons.

During transmission, the complete electromagnetic energy is localized in the subwavelength apertures and thus is intensified several orders of magnitude. At the other side of the sample, the SPP break apart again into electron states and a propagating electromagnetic wave. The result are sharp resonance peaks in transmission at wavelengths which may vastly exceed the spatial dimensions of the holes [12], [13].

The first subwavelength hole structure we considered is shown in Fig. 1 [14]. A single subwavelength hole is surrounded by concentric annular grooves which serve to couple evanescent and propagating modes.

Fig. 1. The sample geometry of a single subwavelength aperture in electromagnetically thick metal film, surrounded by concentric grooves serving to couple plasmon and propagating modes. Top: whole structure; bottom: cross-section of the right hand side

The structure dimensions are chosen to use it in the microwave range: subwavelength hole diameter 2.5 mm, aluminium (conductivity $3.8 \times 10^{-7}$ S/m) thickness is 1.5 mm groove depth is 0.55 mm on each side; the groove width is 1.5 mm.

Another geometry we analyze is an array of slits in thick metal film [15], as shown in Fig. 2. The metal is located on a dielectric substrate. In this geometry, the slits both serve to transmit incident electromagnetic radiation and to couple propagating and surface plasmon modes.

Fig. 2. Array of slits with nanometric thickness in thick metal film

The dimensions of the sample are as follows: metal is gold, described by Drude model, $\varepsilon = \varepsilon_\infty - \omega_p^2 / (\omega^2 + i \gamma \omega)$, $\varepsilon_\infty = 11.46$, $\omega_p = 9.40$ eV, $\gamma = 0.08314$ eV, substrate is glass, $n_{\text{glass}} = 2.25$, slit width is 200 nm, metal stripe width 400 nm, metal thickness 100 nm. We performed our calculations for a sample without dielectric film on the surface (surrounding medium air/vacuum) and for 1 nm and 10 nm thick dielectric films with real part of refractive index $n=1.44$, no losses.

III. RESULTS

First we performed our calculations for the geometry shown in Fig. 1 for microwave radiation in the range (50 - 75) MHz. Radiation is normally incident upon the metal surface and is arriving from below.

Fig. 3. Normalized electric field near the resonant frequency (5.6 mm) calculated by FEM.

Fig. 3 shows the spatial distribution of the time-averaged electric field within the subwavelength hole and around it. Due to the action of the grooves the electric field is redistributed so that it is enhanced in the vicinity of the hole.

Calculations also show that transmission through the same subwavelength hole, but without concentric grooves is extremely low (less than 0.1%). This means that the main cause of the microwave redistribution is the existence of surface corrugations which couple propagating and plasmon modes.
Our next calculations were dedicated to a sample for the optical wavelengths (a case with a larger practical interest for plasmon sensors) with its layout shown in Fig. 2.

Fig. 4 shows calculated values of $|E_z|^2$ for a subwavelength slit array (as shown in Fig. 2) illuminated from below by an optical wave with a wavelength in the range (610-700) nm. The dependence is shown for several wavelengths. For The electric field maximum is observed at a wavelength of 670 nm. The field maxima are located near the walls of the slits. The calculation is done for the case without a dielectric film.

![Fig. 4. Calculated value $|E_z|^2$ through an array of slits in metal film at different wavelengths: no dielectric film on the surface](image)

The next calculation is done for the case when there is a 10 nm thick dielectric film on the surface. The film permittivity is $\varepsilon=1.44$. A similar dependence of the field is observed in Fig. 5 as in the previous case, but the fields are somewhat lower. It can be seen that some spatial redistribution of the fields also occurs.

![Fig. 5. Calculated value of $|E_z|^2$ through an array of slits in metal film at different wavelengths. Dielectric film thickness is 10 nm.](image)

A distribution of the electric fields at metal surface at a cross-section point near the slit wall is shown in Fig. 6.

![Fig. 6. $|E_z|^2$ at different wavelengths at a cross-section point near the subwavelength slit edge for the structure shown in Fig. 2](image)

The change of electromagnetic behavior of the subwavelength slit structure introduced by the modeled adlayer of 10 nm can be seen in Fig. 7. Red line (dashed) denotes the case with the nanolayer, and blue (solid) without it. The difference is noticeable, although neither the structure nor the readout electromagnetic wave parameters were optimized (which will be one of the subjects of our further research).

![Fig. 7. $|E_z|^2$ at the wavelength of 670 nm for the case without a dielectric layer and with a 10 nm adlayer; the structure and parameters are identical to those in Fig. 6](image)

Typical approach to the experimental measurement of structures similar to the above models is to use near-field probes [15], thus directly reading out the presented dependences.
IV. Conclusion

We modeled subwavelength hole and slit arrays without and with a thin (compared to the wavelength used) dielectric layer in order to assess their applicability for plasmon sensors, but also to analyze their behavior generally. The FEM approach used is especially convenient for more complex patterns and structures (for instance, various metasurfaces and metamaterials, but generally plasmonic and nanoplasmonic structures to which EOT subwavelength aperture arrays belong). We intend to direct our future research to the analysis of these more complex structures and their behavior. Since resonant frequency can be tuned by a choice of the surface profile, this offers an additional degree of freedom when designing and utilizing such structures.

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References