Plasmon-Assisted Scattering of Light by a Discrete Corner Made of Silver Nanowires

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Abstract: We consider the problem of the H-polarized plane wave scattering by a discrete corner made of circular wires, using the field expansions in local coordinates and addition theorems for cylindrical functions. The scattering cross-sections and near-field patterns are found numerically and plasmon and grating-type resonances are studied for the corners of nano-size silver wires.

Discrete periodically structured media, or "electromagnetic bandgap materials," are important in today's research into the electromagnetic wave propagation because of the stopband phenomena. Finite scatterers made of periodic elements are even more interesting objects of research as they display much greater dispersion than the similar homogeneous sctatterers. The frequency-selective behavior is usually based on the exploitation of resonances. As known, periodicity may lead to specific resonant phenomena. Among several kinds of resonances observed in periodic structures, important role is played by the so-called grating (G) resonances [1-2]. Their frequencies are just below the Rayleigh frequencies [3] (period being a multiple of the wavelength) if the wires diameter is a fraction of the period. In the wave scattering by infinite wire gratings, they lead to almost total reflection of the incident field by a thin-wire grating in a narrow frequency band.

Another type of resonances is observed in the mid-infrared and optical bands [4]. This is the so-called localized plasmon (P) resonance. It is known that small material objects can exhibit resonance behavior at certain frequencies for which the object permittivity is negative and the free-space wavelength is large in comparison to object dimensions. The latter condition clearly suggests that these resonances are electrostatic in nature [5]. For sub-wavelength metallic objects, P-resonances result in powerful enhancement of scattered and absorbed light that is used in the design of optical antennas and biosensors for advanced applications. Thus, P-resonances have unique physical property: in the leading terms, resonance frequencies depend on the object shape but not depend on its dimensions. In [6], we have studied the effect of G-resonances on the plasmon-assisted scattering by finite flat gratings of sub-wavelength silver wires.

Here we consider the scattering of the H-polarized plane wave by grids of finite number M silver wires which compose discrete corners as shown in Fig. 1. The distance between wires in the side rays is ρ. The wires are circular cylinders with the same radius a and relative dielectric permittivity ε. For particles or wires in the range of tens of nanometers one can use the bulk experimental data published in [7] to characterize the complex dielectric function of silver.

For a 2-D problem, a scalar function U, which represents H_z scattered-field component, must satisfy the Helmholtz equation with wavenumber $k_- = \sqrt{\varepsilon} k_0$ or $k_+ = k_0$ inside and outside of each cylinder, the total tangential field continuity conditions, the radiation condition at infinity, and the condition of the local power finiteness. The solution can be obtained by expanding the field function in terms of the azimuth exponents in the local coordinates, using addition theorems for cylindrical functions, and applying the boundary conditions on all M cylinders. The unknown coefficients related to the q-th cylinder include the effect of all interactions between cylinders. They satisfy a $M \times M$ block-type Fredholm second kind matrix equation, where each block is infinite. Therefore the solution of corresponding counterpart equation with each block truncated to finite order N converges to exact one if $N \to \infty$.

To characterize far-field scattering properties of considered grids we have used the total scattering cross section (TSCS) frequency dependences and far-field scattering patterns; we have calculated the field patterns in the near-field zone.

Figs. 1-3 present results for discrete corners made from silver wires with a = 50 nm. In Fig. 1, presented are TSCSs per one wire as functions of wavelength for discrete right corners (α = π/4) with period 435 nm made from 21 and 101 wires.

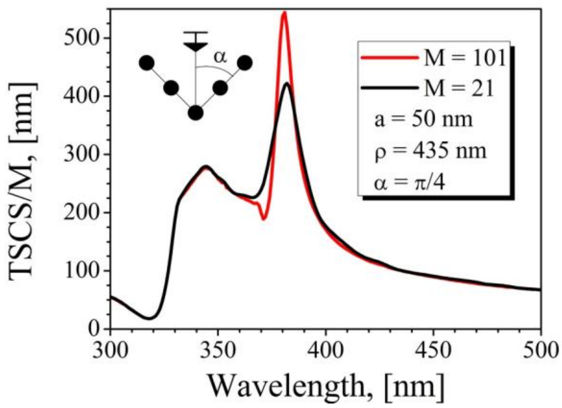

Fig. 1. Normalized TSCS as function of wavelength for H-wave scattering by discrete right corner made of 21 and 101 silver nanowires with radii a = 50 nm, period ρ = 435 nm.

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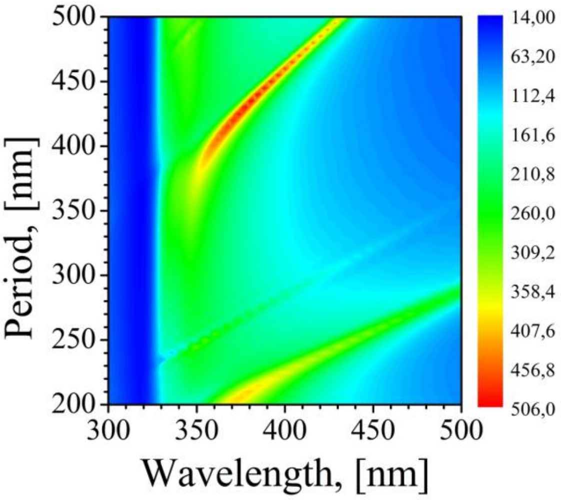

Fig. 2. Relief of normalized TSCS as a function of wavelength and period for H-wave scattering by discrete right corner made of 51 silver nanowires with a = 50 nm.

One can see two resonances for both cases. The first resonance is at the wavelength of 344 nm; this is P-resonance which can be observed for stand-alone wire. The second resonance is at wavelengths 382 nm and 381 nm correspondingly for 21- and 101-wire grid. This is a G-type resonance as the TSCS resonant value gets greater for larger M. Because of grid shape, which is in our case right corner, resonant wavelength is not approximately equal to the period, as it is for linear gratings.

Our numerical simulations confirm that such discrete corner with ρ = 435 takes on maximum values of TSCS. In Fig. 2, presented is relief of TSCS as function of two parameters: wavelength and grid period for discrete right corners made of 51 silver wires. On this relief one can see an area of high TSCS values – it is gaps of grating resonances.

In Fig. 3, presented are near-field amplitude distributions for right discrete corners made of 21 silver wires at the G-resonance wavelength 382 nm for two cases: $\alpha = \pi/4$ and $3\pi/4$. They represent configurations with the incident wave coming from the internal (Fig. 3a) and external (Fig. 3b) sides of the corner along the symmetry axis. One can see that in the case shown in Fig. 3a, there are several "hot spots" near the wires from the illuminated side of the corner rays. On the amplitude pattern shown in Fig. 3b, there is only one "hot spot" at the shadow side of central wire with amplitude in 1.4 times higher than maximum amplitude values in Fig. 3a.

Thus, in this paper we have presented accurate results for the H-polarized wave diffraction by a discrete corner made of silver nanowires. We have investigated two types of resonances: plasmon and grating-type and computed far-field and near-field scattering characteristics of such corners. An interesting observation is the "hot spot" near the central wire on its shadow side in the near-field pattern if incident wave comes from the external side of discrete corner.

This work was supported by the Ukrainian State Target Program "Nanotechnologies and Nanomaterials" and the European Science Foundation via the Networking Programme "Newfocus."

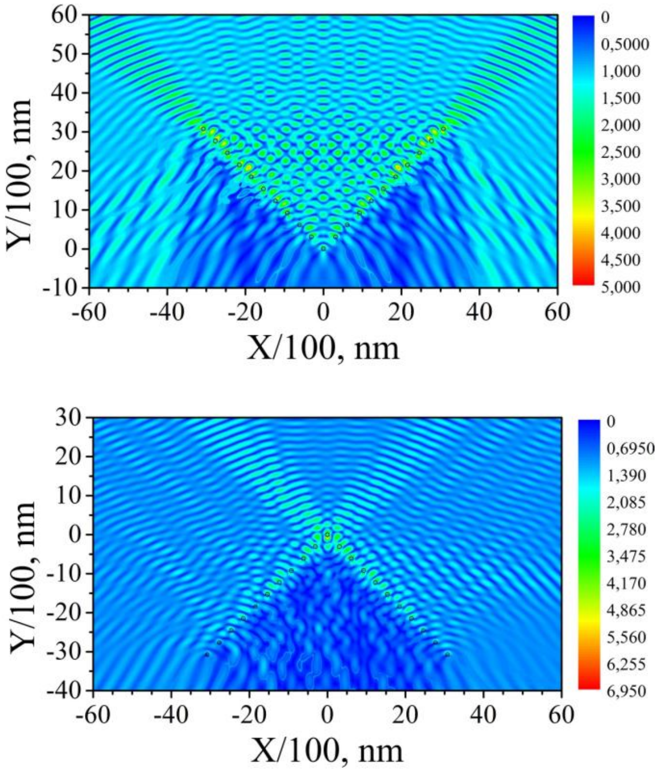

Fig. 3. In-resonance near-field amplitude distribution for H-wave normal incidence by discrete corner made of 21 silver nanowires with a = 50 nm, ρ = 435 nm, λ = 382 nm, $\alpha = \pi/4$ (upper panel) and $\alpha = 3\pi/4$ (lower panel).

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