Theoretical Study of Plasmon Resonances in Linear Chain of Silver Nanowires

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Abstract: In this paper we investigate the plasmon resonance coupling in linear chain of infinite silver nanowires. It was shown the dependence of the resonant peaks location and their magnitudes on the illumination direction and on the distance between the nanowires. The Mie series expansion is used to derive the solution.

In recent years nanooptics and nanotechnology have been considered as a priority in science and technology. The development of nanofabrication together with new achievements in nanotechnology are stimulating the interest in the propagation and scattering of electromagnetic waves in metallic nanostructures.

Plasmonic structures and their optical fields have been the subject of significant interest in recent years. Using resonators composed of negative permittivity materials such as plasma can form the basis of effective small-size antenna elements [1]. Various elements such as plasmonic waveguides [2], subwavelength resonators [3] and optical nanoantennas [4] have been studied recently. Plasmonic structures of different shapes (nanowires, nanorods, nanospheres, nanoshells) are provided by various fabrication techniques.

The interaction of metals with electromagnetic radiation is largely dictated by the free conduction electrons in the metal. Most metals possess a negative dielectric constant at optical frequency as the plasma frequency of the conduction electron gas lies in this range [5] which causes, for example, a very high reflectivity. Furthermore, at optical frequencies the metals can sustain surface oscillations called plasmon polaritons or plasmons with distinct resonance frequencies. The existence of plasmons is characteristic of the interaction of metal nanostructures with light. Similar behavior cannot be simply reproduced in other spectral ranges using the scale invariance of Maxwell's equations since the material parameter change considerably with frequency [6].

The objective of this paper is to analyze the plasmonic resonances in finite array of silver coupled nanowires. For this we consider H-polarized plane wave scattering on a linear chain of N identical equidistant infinite-long silver cylindrical nanowires with separation distance *d*. Frequency-domain solution of the Maxwell equations is obtained. We present the internal field

$$H(\rho_j,\varphi_j)=\sum_{s=-\infty}^{+\infty} a_s^{(j)} J_s(\bar{k}\rho_j)e^{is\varphi j}$$

and the external field

$$H(\rho_j,\varphi_j)=\sum_{j=1}^{N}\sum_{s=-\infty}^{+\infty} b_s^{(j)} H_s^{(2)}(k\rho_j)e^{is\varphi j}+e^{-ikx}$$

using Mie's series expansions.

Here (ρ_j,φ_j) are set of N polar systems of coordinates, associated with each nanowire ($j=1...N$), time dependence is $e^{i\omega t}$, $\bar{k}=\bar{n}\,\omega/c$, $k=\omega/c$, $\bar{n}$ is the refractive index of silver, x-axis is directed along the major axis of the structure.

For the refractive index $\bar{n}(\lambda)=n'(\lambda)-in''(\lambda)$ we use the experimental data obtained by Jonson and Christie [7] for bulk silver.

Unknown coefficients $a_s^{(j)}$ and $b_s^{(j)}$ are found from the boundary conditions, requiring the tangential components of the total electric and magnetic fields to be continuous at each nanowire's surface. Using the addition theorem for Bessel functions we arrive at an infinite system of algebraic equations that can be truncated in order to provide a controlled numerical precision.

Fig. 1 illustrates the propagation of light in the structure of N=4 coupled nanowires with 50 nm diameter and 5 nm separation distance. Plasmonic resonance is excited at $\lambda=380$ nm wavelength. Optical field enhancement in the last gap between the wires is observable.

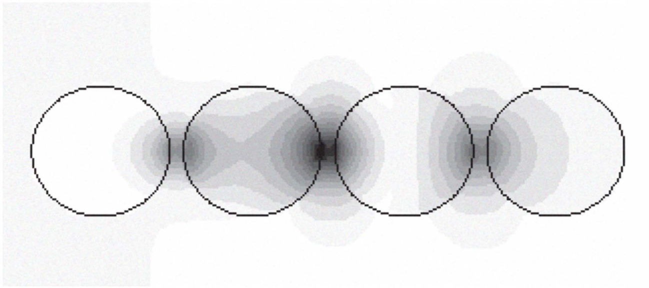

Fig. 1. Near field distribution of plane wave scattering on chain of silver nanowires (illumination along major axis).

The scattering cross sections for the N=4 coupled nanowires are shown in Fig. 2 (illumination is along major axis of the structure) and in Fig. 3 (illumination is normal to the major axis). It is seen the resonance peak at λ=340 nm

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for d=5 nm for both directions of incidence and different separation distances.

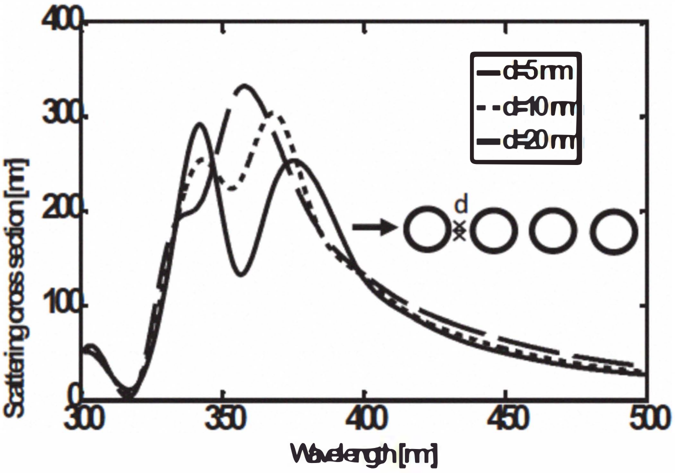

Fig. 2. Scattering cross section of four 50 nm diameter cylinders with different separation distances. Illumination is directed along the major axis of the structure.

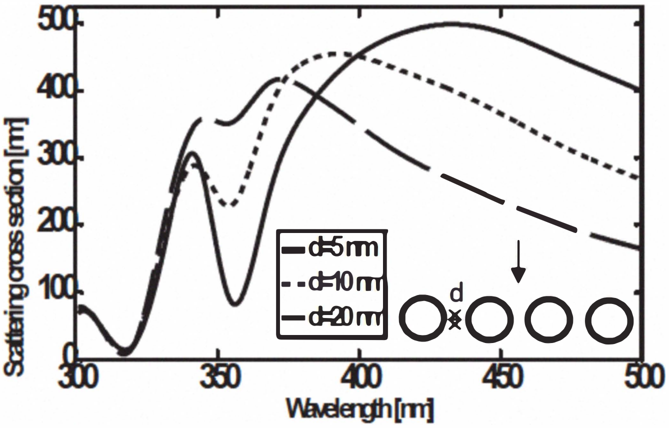

Fig. 3. Scattering cross section of four 50 nm diameter cylinders with different separation distances. Illumination is normal to the major axis.

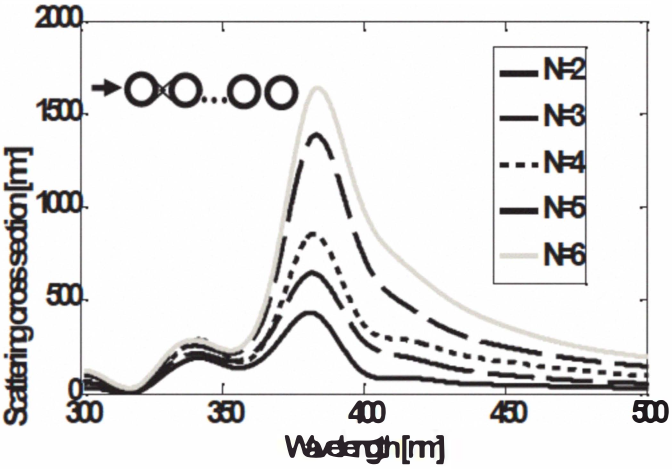

Fig. 4. Scattering cross section of two, three, four, five and six 30 nm diameter cylinders with a 6 nm separation. Illumination is along the major axis.

Besides we observe appearance of additional resonances. It is seen the red-shift of this resonance with decreasing of the separation distance between the cylinders: λ =355 nm for d = 20 nm; λ =370 nm for d = 10 nm and λ =380 nm for d = 5 nm for illumination along major axis (Fig. 2). With growing of the separation distance we will observe only one resonant peak [5]. Fig. 3 shows the red-shift of the main resonance with decreasing of separation distance between the cylinders: λ =370 nm for d = 20 nm, λ =390 nm for d = 10 nm and λ =440 nm for d = 5 nm. We see the broadening of this resonance peak when nanowires are brought together. It is seen that for normal incidence the coupling effect is much stronger.

Fig. 4 demonstrates the scattering cross section versus the wavelenght for various number of nanowires in a chain. We see increasing of the distance between the resonant peaks with growing the number of wires (λ =342 and λ =380 nm for N = 2; λ =341.5 and λ =381 nm for N = 3; λ =341 and 382 nm for N = 4; λ =340.5 and 383 nm for N = 5; λ =340 and 385 nm for N = 6).

In conclusion, theoretical study of plasmon resonances in a finite linear array of infinite-long silver nanowires is presented. The attention is focused on the spectral response and optical near fields. Spectral shift upon the growing of the number of nanowires in an array has been shown.

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REFERENCES

[1] H. R. Stuart, A. Pidwerbetsky: Electrically small antenna elements using negative permittivity resonators, *IEEE Trans. Antennas and Propagation*, vol. 54, pp. 1644-1653, 2006.

[2] Y. Zhao, et.al.: Finite-difference time-domain study of guided modes in nano-plasmonic waveguides. *IEEE Trans. Antennas Propag.*, vol. 55, Pp. 3070-3077, Nov. 2007.

[3] J. li and N. Engheta: Ultracompact sub-wavelength plasmonic cavity resonator on a nanowire, *Phys. Rev. B*, vol. 74, 115125, 2006.

[4] P. Muhlschlegel, et.al.: Resonant optical antennas, *Science*, vol. 308, pp. 1607-1609, 2005.

[5] J. Kottmann and O. Martin: Plasmon resonant coupling in metallic nanowires, *Optics Express*, vol. 8, pp. 655-663, 2001.

[6] L.Novotny, B. Hecht, Principles of Nano-Optics, Cambridge University Press, 2006, pp. 378-410.

[7] P. Jonson and R. Christy, Optical constants of the noble metals, *Phys. Rev. B*, vol. 6, pp. 4370-4379, 1972.