Transmission of Enhanced Optical Responses through a Linkage of Surface Plasmon Resonances in a Finite Periodic Array of Metallic Nanocylinders

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***Abstract* – Two-dimensional scattering of TE polarized light by a finite periodic array of metallic nanocylinders is investigated by using a model of arrays of circular cylinders periodically distributed on layered circular rings.**

***Index Terms* - Optical responses, finite array of metallic nanocylinders, resonant interactions, localized surface plasmons.**

I. INTRODUCTION

With the development of nanoscience and nanotechnology, the interaction of light with nanoscale objects [1] remains as an important topic in recent years because of their wide applications to optical sensors, imaging, and integrated devices. Among others, the enhanced surface plasmon resonances [2],[3] in noble metallic nanocylinder systems is expected to be a promising issue for realizing excellent scatterers and absorbers of visible light that may be used in manipulating of optical responses beyond the diffraction limit.

In this paper, we shall investigate two-dimensional scatterings of TE polarized plane waves by a finite linear array formed by periodically arranged circular metallic nano-cylinders of infinite length. The scattering problem is formulated [4],[5] by using a model of arrays of circular cylinders periodically distributed on layered circular rings. The scattering and absorption cross sections and the near field distributions are calculated for the finite array of Ag nanocylinders and compared with those obtained for the same array geometry consisting of dielectric nanocylinders. The numerical examples demonstrate that the enhanced optical near field responses can be transmitted along the array through a linkage of the localized surface plasmon resonances excited on each of nanocylinders when the array is illuminated by the TE plane wave with a particular wavelength.

II. FORMULATION OF THE PROBLEM

The cross section of a periodic linear array consisting of circular nanocylinders located in a background medium with material constants ε_0 and μ_0 is shown in Fig. 1. The $2N+1$ cylinders with the radius r and the relative permittivity ε_r are infinitely long in the z direction and distributed with the period h in

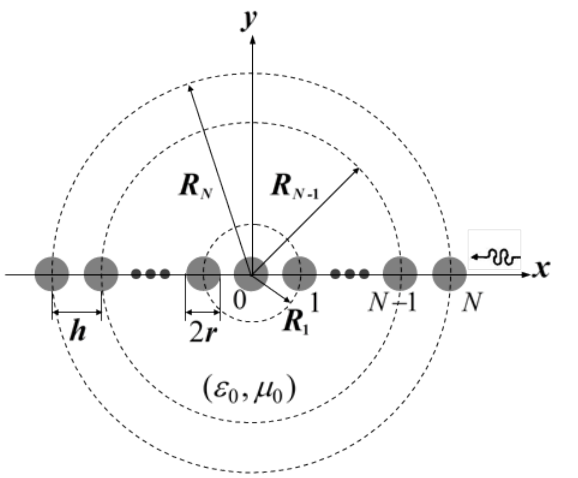


Fig. 1. Cross section of a periodic linear array of $2N+1$ circular nanocylinders and the model of N- layered cylindrical arrays consisting of two nanocylinders symmetrically distributed on each of N concentric circular rings with radii $R_\nu = \nu h \, (\nu = 1, 2, \cdots, N)$.

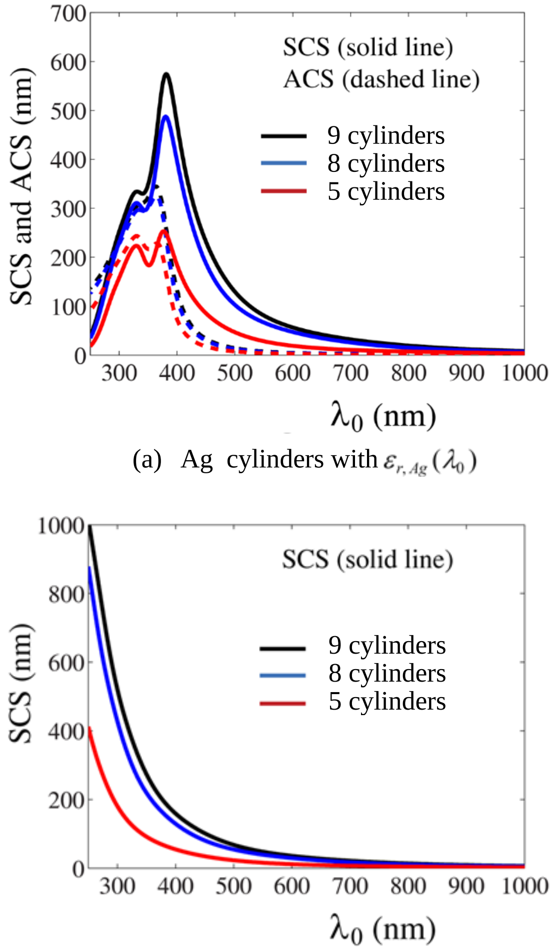
the x direction. We shall analyze the scattered field from this finite periodic array when illuminated by the TE (E_x, E_y, H_z) plane wave propagating in the $-x$ direction by using the model of layered cylindrically periodic arrays in which two cylinders are symmetrically located on each of N concentric circular rings with the radii $R_\nu = \nu h$ $(\nu = 1, 2, \cdots, N)$ as depicted by the dotted lines in Fig. 1. The additional one cylinder is placed in the global center of the concentric cylindrical structure to complete the array of $2N+1$ cylinders. When the array consists of $2N$ cylinders, we can remove the #0 cylinder located at the center and set the radii of each circular rings to be $R_\nu = (2\nu - 1)h/2$ $(\nu = 1, 2, \cdots, N)$.

Using the model of N- layered cylindrically periodic arrays, the scattering process in a linear array of $2N+1$ cylinders can be formulated by the T-matrix of the circular cylinder in isolation, the reflection and transmission matrices based on the cylindrical waves at each of N concentric circular rings, and the generalized reflection and transmission matrices over the N- layered structure. The semi-analytical procedure to be used for the layered cylindrically periodic arrays of circular cylinders is well documented in [4] and [5].

III. NUMERICAL EXAMPLES

Although a substantial number of numerical examples could be generated, we investigate here a linear array consisting of 9, 8, or 5 nanocylinders with $r = 25nm$ and $h = 55nm$. The material of nanocylinders is assumed to be silver (Ag) with $\varepsilon_{r,Ag}(\lambda_0)$ or a dielectric with $\varepsilon_r = 6.5$. It is known that the permittivity of a noble metal in optical region has a complex value with a negative real part and a small imaginary part. The value of the real part strongly depends on the wavelength λ_0. The proper evaluation of $\varepsilon_{r,Ag}(\lambda_0)$ is crucial in the present analysis. We employ here the Drude-Lorentz model with the fitting parameters [6] for Ag.

The scattering cross section (SCS) and absorption cross section (ACS) of the arrays of three different numbers of cylinders are plotted in Fig. 2 as functions of the wavelength λ_0 of the incident wave for (a) Ag cylinders and (b) dielectric cylinders with $\varepsilon_r = 6.5$. We can see that SCS and ACS of the array of Ag cylinders exhibit a resonant behavior as functions of wavelength λ_0, whereas SCS of the array of dielectric cylinders does monotonic responses. The SCS of the array of Ag cylinders has a peak at λ_0=381nm and its resonant behaviour is significantly enhanced as the number of cylinders increases. The wavelength 381nm corresponds to the gap plasmon resonances [7],[8] in the array of Ag cylinders in close proximity, which are excited in the gap region through the surface plasmon resonant coupling between adjacent Ag cylinders. The strong coupling is attained for a particular wavelength depending on the separation distance between Ag cylinders.

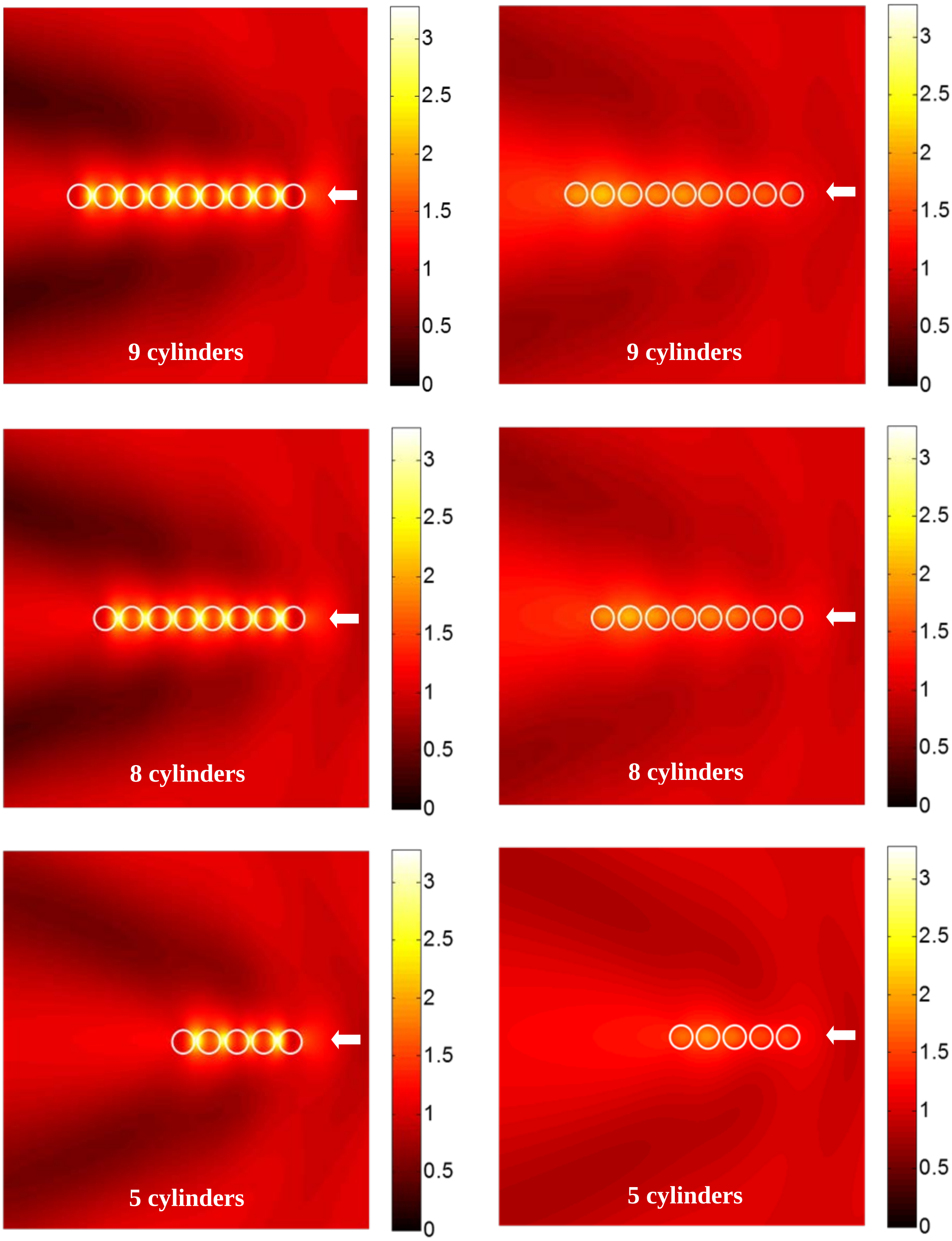


(a) Ag cylinders with $\varepsilon_{r,Ag}(\lambda_0)$

(b) Dielectric cylinders with ε_r=6.5

Fig. 2. Scattering and absorption cross sections (SCS and ACS) of the arrays of three different numbers of cylinders as functions of the wavelength λ_0 of excitation for (a) Ag cylinders and (b) dielectric cylinders with ε_r=6.5, where r=25nm and h=55nm.

The incident wave resonates to the gap plasmon modes under special wavelengths and enhances a harmonic collective motion of electrons located near the boundary surfaces of Ag cylinders. The harmonic motion of electrons absorbs the incident wave energy through their collisions and also acts as a source for the scattered field. The small difference in the wavelengths at which SCS and ACS have peak values may be considered as a result of use of



(a) Ag cylinders (b) Dielectric cylinders with $\varepsilon_r = 6.5$

Fig. 3. Near field distributions of $|H_z^t|$ for the linear arrays consisting of 9, 8, and 5 nanocylinders with $r = 25nm$ and $h = 55nm$ which are illuminated by TE plane wave of $\lambda_0 = 381nm$ propagating in the direction of white arrows: (a) Ag cylinders and (b) dielectric cylinders with $\varepsilon_r = 6.5$. The wavelength $\lambda_0 = 381nm$ corresponds to the wavelength at which the SCS takes a peak value in Figs. 2(a).

Drude-Lorentz model for Ag which combines two different dispersion model of electrons. In order to confirm the phenomena of the gap plasmon resonances in the array of Ag nanocylinders, we have calculated near field distributions of $|H_z^t| = |H_z^i + H_z^s|$ under the illumination by TE plane wave of λ_0=381*nm* and a unit amplitude, where H_z^i and H_z^s denote the incident and scattered H_z fields, respectively.

The near field distributions obtained for the arrays of Ag nanocylinders are shown in Fig. 3 and compared with those obtained for the array of dielectric nanocylinders with ε_r=6.5 . We can see that the responses of Ag nanocylinders and dielectric nanocylinders to the excitation by the plane wave are quite different, though both array structures have the same geometrical parameters. The enhanced field pattern are periodically observed in the gap regions for the array of Ag nanocylinders. This unique response indicates the excitation of the localized gap plasmons because the end of the array structure does not influence the field distributions. It is worth noting that the near field distributions are almost identical over the array lengths for the array of 9, 8, and 5 nanocylinders. If the gap plasmon was a propagating mode, there would appear the end effects of the array and some kind of standing wave patterns would be formed through the interference between the forward and backward waves along the finite array. We can observe such standing wave patterns for the array of dielectric nanocylinders shown in Fig. 3(b).

Finally, Fig. 4 shows the near field distributions of $|H_z^t|$ for the linear array of 9 nanocylinders of Ag with r=25*nm* and h=55*nm* , which is illuminated by TE plane wave of λ_0=328*nm* and a unit amplitude. The array structure is the same as shown in the top figure of Fig. 3(a) but the wavelength of excitation is far from the gap plasmon resonance wavelength λ_0=381*nm* . We can see that the array of Ag nanocylinders does not exhibit any response to the illumination at λ_0=328*nm* .

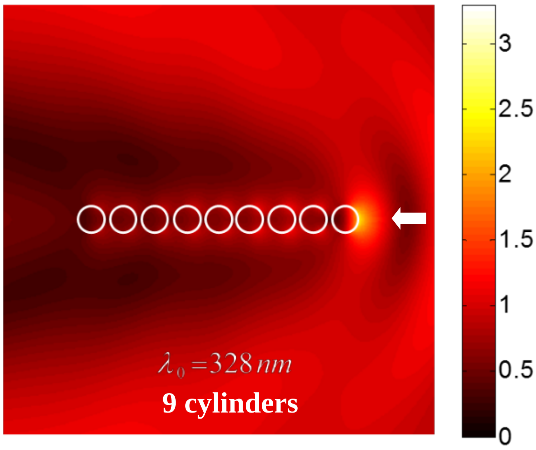


Fig. 4. Near field distribution of $|H_z^t|$ for the linear array of 9 nanocylinders of Ag with r=25*nm* and h=55*nm* . The array is illuminated by the plane wave of λ_0=328*nm* which is far from the resonance wavelength λ_0=381*nm* .

IV. CONCLUSION

The scattering of TE plane wave by a linear periodic array of Ag nanocylinders was investigated by using the model of arrays of circular cylinders periodically distributed on layered circular rings. From the analysis of scattering and absorption cross sections and the near field distributions, it was shown that the enhanced optical responses can be transmitted through a linkage of localized surface plasmon resonances in a finite periodic array of Ag nanocylinders. This unique features of metallic nanocylinders may be used for manipulating optical fields beyond the diffraction limit.

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