Scattering of light by periodic array of metal-coated nanocylinders on dielectric slab

Yasumoto, Kiyotoshi; Jandieri, Vakhtang; Meng, Peiwen; Liu, Yunfei

Publication date
2017

Document Version
Final published version

Published in
ISAP 2016 - International Symposium on Antennas and Propagation

Citation (APA)
Yasumoto, K., Jandieri, V., Meng, P., & Liu, Y. (2017). Scattering of light by periodic array of metal-coated nanocylinders on dielectric slab. In T. Uno, N. Kikuma, H. Arai, & K. Cho (Eds.), *ISAP 2016 - International Symposium on Antennas and Propagation* (pp. 572-573). Article 7821208 IEEE.

Proceedings of ISAP2016, Okinawa, Japan

Scattering of Light by Periodic Array of Metal-Coated Nanocylinders on Dielectric Slab

Kiyotoshi Yasumoto[1], Vakhtang Jandieri[2], Peiwen Meng[3], and Yunfei Liu[1]
[1]College of Information Science and Technology, Nanjing Forestry University, Nanjing, China
[2]Department of Electrical and Computer Engineering, Free University of Tbilisi, Tbilisi, Republic of Georgia
[3]Department of Imaging Physics, Delft University of Technology, Delft, Zuid-Holland, Netherlands

Abstract – **Scattering of light by a periodic array of metal-coated nanocylinders located on a dielectric slab is analyzed by using a semi-analytical method based on a recursive algorithm combined with the lattice sums technique. The resonance phenomena observed in the spectral responses of the scattered field are numerically investigated.**

Index Terms — **Metal-coated nanocylinder, Periodic array, Light wave, Resonant scattering.**

1. Introduction

With a rapid development of nanoscience and nanotechnology, the interaction of light with nanoscaled metallic objects remains as an important issue in recent years [1] because of its wide range applications to optical sensors, imaging, and integrated photonic devices. The literature on the interaction of light with nanoscaled objects is much broader. The studies on the interaction are organized in many different ways, being dependent on the dimensionality of the objects and exciting sources.

In this paper, we shall analyze the scattering of TE polarized plane wave by a periodic array of metal-coated nanocylinders located on a dielectric slab by using a semi-analytical method [2] based on the recursive algorithm combined with the lattice sums technique. In this approach, the reflection and transmission matrices of the array is firstly extracted and then a recursive formula is applied to derive the scattering matrix over the whole structure consisting of the grating layer and the dielectric slab. The spectral responses in the power transmission, reflection, and absorption coefficients are numerically investigated and their resonance behaviors are discussed

2. Formulation of the Problem

The cross section of a periodic array of nanocylinders supported on a dielectric slab and situated in a background medium is shown in Fig. 1. The array period is h, the thickness of the dielectric slab is d, and the nanocylinder is a metal-coated circular coaxial cylinder consisting of a dielectric core with radius r_2 and a coating metal layer of thickness $r_1 - r_2$. The material constants of the background medium, dielectric slab, coating metal, and dielectric core are denoted by (ε_B, μ_0), (ε_s, μ_0), (ε_M, μ_0), and (ε_c, μ_0), respectively. The array is illuminated by a TE (H_z, E_x, E_y) polarized plane wave of unit amplitude. The angle of incidence of the plane wave is φ_0.

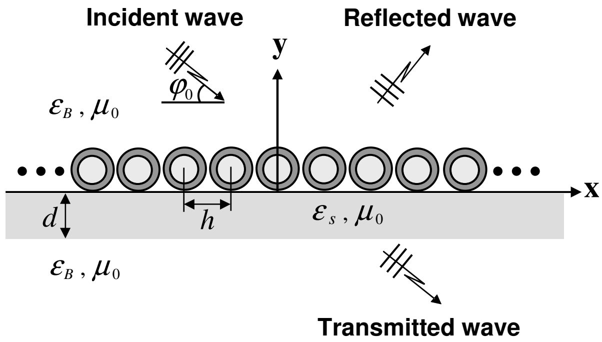

Fig. 1. Cross-sectional view of a periodic array of metal-coated nanocylinders supported on a dielectric slab and illuminated by a TE (E_x, E_y, H_z) polarized plane wave.

The scattering problem is formulated using the T-matrix and lattice sums techniques combined with the recursive formula for the generalized reflection and transmission matrices for a layered structure. Firstly, the T-matrix of the coaxial nanocylinder in isolation is calculated in closed form [3] by using the cylindrical wave expansion. Then the reflection and transmission matrices for the array of nanocylinders are calculated in semi-analytical form [2] by using the lattice sums technique. The matrices are expressed in terms of the space harmonics of the incident plane wave as the basis. The reflection and transmission matrices are concatenated to obtain the generalized reflection and transmission matrices for the layered structure. The structure shown in Fig. 1 consists of four layers formed by the upper background layer with $y > 2r_1$, the grating layer with $0 \le y \le 2r_1$, the slab region with $-d \le y < 0$, and the lower background layer with $y < -d$.

3. Numerical Results and Discussion

Although a substantial number of numerical examples could be generated, we study here the normal incidence (φ_0=90°) of the plane wave on the array of Ag-coated nanocylinders under the structural parameters: $r_1=40nm$, $r_2=20nm$, $h=300nm$, $\varepsilon_c/\varepsilon_0=6.5$, $d=200nm$, and $\varepsilon_s/\varepsilon_0=2.5$. The dispersive permittivity $\varepsilon_M(\lambda)$ of Ag is evaluated using Drude-Lorentz model with the fitting parameters.

Fig. 2 shows the power transmission (P_0^t), reflection (P_0^r), and absorption (P_0^a) coefficients of the zeroth diffraction order as functions of the wavelength in the range

$250nm \le \lambda \le 1000nm$ where the background medium is assumed to be free space with $n_B = \sqrt{\varepsilon_B/\varepsilon_0} = 1.0$. These coefficients are obtained by truncating the diffraction orders by ±20 and satisfy the energy conservation relation within the accuracy of 10^{-8} order. We can see that P_0^t takes minima at four wavelengths as marked in the inset. The sharp resonant dip at λ=300nm indicates Rayleigh anomalies which satisfy the relation $\lambda = n_B h$ for the ±1st diffraction order under the normal incidence (φ_0=90°). A resonant dip at λ=415nm represents the guided mode resonance which occurs when the scattered wave of the m-th diffraction order is in phase matching with the guided modes supported by the dielectric slab. The phase matching between the fundamental TE guided mode of the dielectric slab and the scattered wave of ±1st diffraction order is attained at around λ=415nm for the normal incidence (φ_0=90°) case. Other two moderate resonant dips observed at around λ=335nm and λ=613nm correspond to the localized surface plasmon resonances. The shorter wavelength resonance is related to the plasmon localized on the outer surface of radius r_1 and the longer wavelength resonance is related to the plasmon localized on the inner surface of radius r_2. Fig. 3 shows the near field distribution for the wavelength λ=415nm at which the scattered waves of the ±1st diffraction orders are resonantly coupled to the forward and backward propagating guided modes in the dielectric slab.

The resonant behaviors of power transmission spectra (P_0^t) are compared in Fig. 4 when the refractive index n_B of the background medium is changed. The Rayleigh anomalies are shifted toward the longer wavelengths through the relation $\lambda = n_B h$ as n_B increases. λ = 390nm, 450nm, and 510nm indicate Rayleigh wavelengths for n_B =1.3, 1.5, and 1.7, respectively. The guided mode resonances are also shifted toward longer wavelengths as n_B increases. This is because the effective refractive index for guided modes on the dielectric slab increases with n_B. The wavelengths 436nm and 456nm correspond to the guided mode resonances for n_B =1.3 and 1.5, respectively. When n_B =1.7, the dielectric slab does not support guided waves because $\varepsilon_s < \varepsilon_B$ and the guided mode resonance is not observed in the transmission spectra. The wavelengths for surface plasmons resonances, which were observed at 335nm and 613nm for n_B =1.0, do not show any noticeable changes when n_B is increased. But it is worth mentioning that the dip of transmission spectra at around λ = 613nm is significantly enhanced as n_B increases.

References

[1] J. Zhang and L. Zhang, "Nanostructures for surface plasmons," *Advances in Optics and Photonics*, Vol. 4, No. 2, pp. 157-321, 2012.

[2] K. Yasumoto, H. Toyama, and T. Kushta, "Accurate analysis of two-dimensional electromagnetic scattering from multilayered periodic arrays of circular cylinders using lattice sums technique," *IEEE Trans. Antennas Propagat.*, Vol. 52, No. 10, pp. 2603-2611, 2004.

[3] V. Jandieri, P. Meng, K. Yasumoto, and Y. Liu, "Scattering of light by gratings of metal-coated circular nanocylinders on a dielectric substrate," *J. Opt. Soc. Am. A*, Vol. 32, No. 7, pp. 1384-1389, 2015.

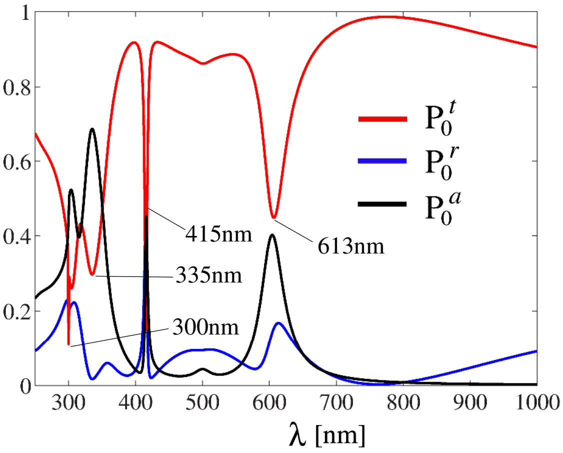

Fig. 2. Power transmission (P_0^t), reflection (P_0^r), and absorption (P_0^a) coefficients of the zeroth diffraction order as functions of wavelength λ where r_1=40nm, r_2=20nm, h=300nm, $\varepsilon_c/\varepsilon_0$=6.5, d=200nm, $\varepsilon_s/\varepsilon_0$=2.5, and the background medium is free space with $n_B = \sqrt{\varepsilon_B/\varepsilon_0} = 1.0$.

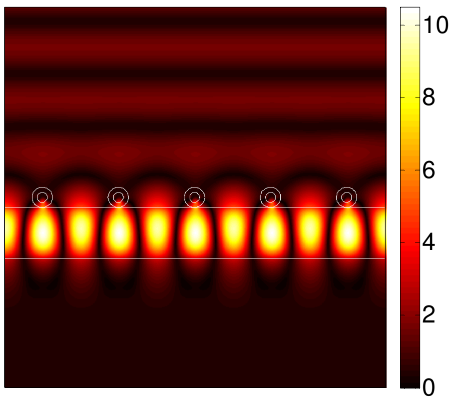

Fig. 3. Near field distribution of $|H_z|$ for λ=415nm at which the guided mode resonance is observed in Fig. 2.

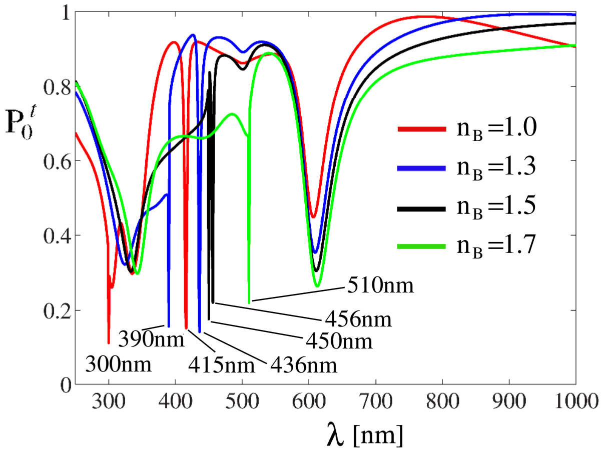

Fig. 4. Power transmission coefficient (P_0^t) as functions of wavelength λ for four different background media with $n_B = \sqrt{\varepsilon_B/\varepsilon_0}$. Other structural parameters are the same as those given in Fig. 2.