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Evanescent wave scattering at off-axis incidence on multiple cylinders located near a surface

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ABSTRACT

The scattering characteristics of an infinite cylinder are strongly influenced by the incidence angle relative to its axis. If the incident wave propagates in the plane normal to the axis of the cylinder, the polarization of the scattered wave remains unchanged and the scattered wave propagates in the same plan as the incident wave. At off-axis incidence such that the incident direction makes an oblique angle with the cylinder axis, the scattered wave is depolarized, and its spatial distribution becomes three-dimensional. This paper presents the scattering solution for oblique incidence on multiple parallel cylinders located near a planar interface by an evanescent wave that is generated by total internal reflection of the source wave propagating in the higher refractive index substrate. Hertz potentials are utilized to formulate the interaction of inhomogeneous waves with the cylinders, scattering at the substrate interface, and near field scattering between the cylinders. Analytic formulas are derived for the electromagnetic fields and Poynting vector of scattered radiation in the near-field and their asymptotic forms in the far-field. Numerical examples are shown to illustrate scattering of evanescent wave by multiple cylinders at off-axis incidence.

1. Introduction

Scattering of an evanescent wave by particles on or near a surface is of significant interests to near-field applications such as scanning optical microscopy, scanning electron microscopy, scanning tunneling microscopy, etc. These applications generally involve particles located on or suspended in an aqueous solution above the surface of a substrate which has a higher refractive index. The particles are irradiated by a surface wave generated by total internal reflection of a light source propagating inside the substrate. The intensity and polarization of the scattered radiation are used to deduce the size and position of the particles.

Many studies have been reported in the literature on evanescent wave scattering by spherical particles in conjunction with optical microscopy applications. Prieve et al. [1,2] developed the technique to study the equilibrium and dynamic behavior of charged particles near flat surfaces. They utilized the variation of the intensity of the scattered light with location to determine the vertical motion of the particle above the interface. Siegel [3] described several applications utilizing evanescent wave scattering to study near-wall dynamics and interactions of colloidal systems. By changing the angle of incidence of the source beam, the penetration depth of the evanescent wave is varied to probe colloidal systems at different length scales [3,4]. The polarization of the scattered wave from particles irradiated by an evanescent wave was

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utilized by Aslan et al. [5] to characterize the particles. Numerical analyses based on the discrete source and T-matrix methods have been used to study evanescent scattering by spherical particles [6–8].

Scattering of an evanescent wave by cylindrical particles on a surface is an important fundamental problem in particle characterization. The scattering characteristics of cylindrical particles with large length-to-diameter ratios are similar to those of infinite cylinders [9], which are a function of the angle of incidence. Existing studies on evanescent wave scattering by infinite cylinders are few and restricted to perpendicular incidence only. They include the numerical solution of the boundary integral equations by Belai et al. [10,11] for one and two cylinders, and the analytic solution utilizing Hertz potentials for multiple cylinders by Lee [12]. In practical problems both the direction of the source wave and the alignment of cylinders are often unrestricted. The incident direction is usually inclined at an oblique angle from the axes of the cylinders, thus resulting in depolarization of the scattered waves and a three-dimensional spatial distribution of the scattered radiation. On the other hand, depolarization does not occur at perpendicular incidence, and the scattered waves propagate in the plane normal to the cylinder axis. A general solution applicable to off-axis incidence is needed for treating realistic scenarios.

The objective of this paper is to present an analytical solution applicable to both homogeneous and evanescent waves at off-axis incidence on multiple infinite cylinders located near the surface of a substrate. The source radiation is an arbitrarily polarized plane wave propagating inside the substrate in a general direction at the cylinders. For generality each cylinder is radially stratified and distinct, and no restriction is placed on their size and location. The pertinent phenomena of depolarization of scattered waves, Fresnel reflection at the interface, and near field scattering are rigorously treated in the theoretical formulation that is detailed in Section 2. Numerical examples to illustrate off-axis incidence on multiple cylinders are given in Section 3, followed by a summary of the pertinent aspects of the present study in Section 4.

2. Theory

A schematic diagram of the present problem is shown in Fig. 1. An arbitrary configuration of distinct, radially stratified infinite cylinders is located in medium 2 near the medium 2–1 interface. Both media 1 and 2 are non-absorbing dielectrics with real refractive indexes $\tilde{m}_1$ and $\tilde{m}_2$, respectively, and $\tilde{m}_1 > \tilde{m}_2$. An arbitrarily polarized source wave propagates in medium 1 in the direction prescribed by the azimuth angle θ_1 measured in, and the polar angle ϕ_1 inclined from, the *XY* plane, whereas the cylinders are aligned parallel to the *Z*-axis. Off-axis or oblique incidence refers to $\phi_1 > 0$, for which the incident direction is not confined to the *XY* plane that is perpendicular to the axes of the cylinders.

The scattering interactions near the interface are depicted in Fig. 2. The transmitted source wave into medium 2, which can be a homogeneous or an evanescent wave depending on whether the critical angle is exceeded, is the primary incident wave on the cylinders. The scattered waves from the cylinders give rise to secondary and tertiary incident waves on the cylinders. The former arises from the near-field scattered waves from other cylinders, and the latter is due to reflection of the scattered waves at the medium 2–1 interface. In addition, the scattered waves are depolarized at oblique incidence, thus giving rise to cross polarization modes that contribute to the secondary and tertiary incident waves.

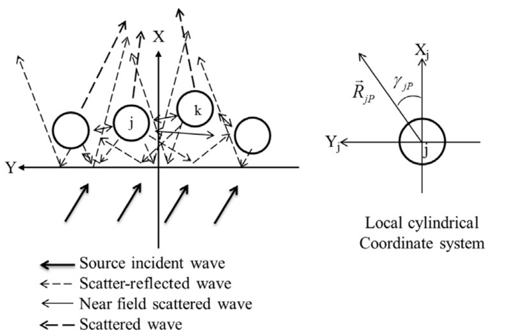

Fig. 2. Scattering interactions for cylinders located near a surface.

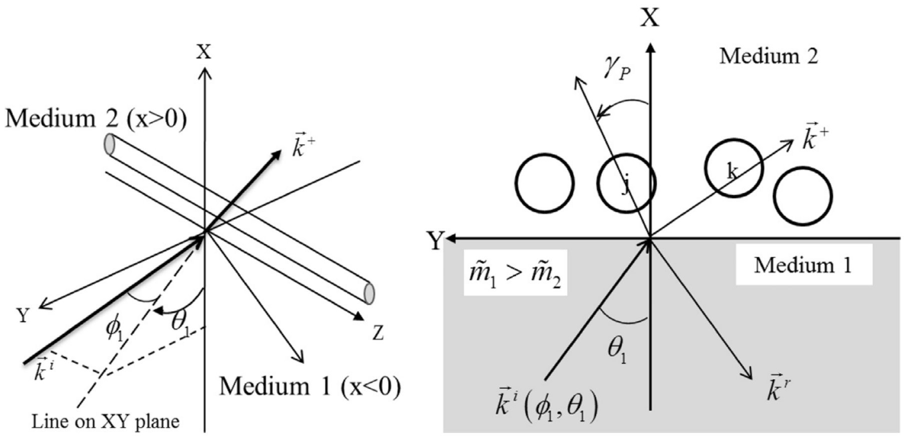

Fig. 1. Schematic diagram of the present problem.