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Electromagnetic scattering from gyroelectric anisotropic particle by the T-matrix method

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ABSTRACT

A T-matrix solution is developed for the aim of predicting the electromagnetic scattering behaviors from a nonspherical gyroelectric particle. The theoretical treatments is implemented within the framework of the extended boundary condition method (EBCM), where a system of quasi-spherical vector wave functions (qSVWFs) for expanding electromagnetic fields inside gyroelectric media is derived by using an inverse Fourier transform operation. As verification, comparisons are made between numerical results obtained using the presented method and those published data calculated using other methods. Very good agreements are achieved for the present cases, which partially indicate the correctness of the derived theoretical formulae and the home-made program. Influences of shape deformation as well as of anisotropy components in permittivity tensor upon the scattering properties are then analyzed. Numerical results show that a dramatic decrease in radar cross sections (RCSs) level occurs when the gyroelectric cross terms are included in the permittivity tensor, and a clear shift of peaks in RCSs to smaller angles is displayed as a prolate spheroid is deformed to an oblate spheroid.

1. Introduction

In recent years, the analysis of interactions between electromagnetic waves and anisotropic media is a great hotspot in research, which is mostly due to the existence of various natural anisotropic crystals and possible realization of artificial anisotropic composites. The promising applications of anisotropic material can be found in various fields, especially in wireless communication technologies and biological fields [1–4].

Among the anisotropic media, a special subclass which is known as gyrotropic anisotropic medium, e.g. magnetized plasma, has attracted a lot of interest. The plasma is a medium consists of gas in highly ionized state, and also a neutral mixture of free ions, electrons and molecules. For instance, when a satellite comes into atmosphere, there is a natural sheath of plasma over it. In the laboratory situation, the normal plasma can be approximated by a lossy isotropic medium with a complex permittivity. Nevertheless, the plasma is magnetized once it is presented in an exterior magnetic field and it turns to be a special gyroelectric anisotropic medium whose permittivity takes a tensor form without symmetry. The elements of the permittivity tensor are complex functions of wave, gyro and collision frequencies. Since the plasma has shown its potential applications in the field of microwave and antennas, such as optical signal processing, the control of radar cross sections for military objects, development of certain types of radar absorbers, and so on, the electromagnetic characteristics of the plasma as well as other gyroelectric anisotropic media attracted lots of attention.

In the characteristics of anisotropic media, one of the basic problems is to investigate the interaction between electromagnetic waves and anisotropic media. Various methods are developed to deal with this problem in the past decades. On one hand, some numerical computation

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approaches, including the finite element method (FEM) [5], the finite-difference time-domain method (FDTD) [6], the methods of moments (MoM) [7], the discrete dipole approximation (DDA) [8] and so on, were widely applied since their capability in handling electromagnetic scattering from objects with arbitrary permittivity tensor and arbitrary shape. Nevertheless, these numerical methods, which employed computational techniques to deal with the meshed problems for numerical solution, were considered not effective enough in computations and also encountered a limitation in dealing with objects of large size parameter, for instance, particles in the range of optical resonance region. On the other hand, some analytical approaches, which provided accurate and more effective ways, were also developed. For instance, by using an extended Mie theory with the Fourier transform, scattering properties from a uniaxial anisotropic sphere [9], uniaxial coated sphere [10], aggregate of uniaxial anisotropic spheres [11], a magnetized plasma sphere [12] and a layered magnetized plasma sphere [13] were studied. An extension of this method to the analysis of scattering from a uniaxial cylinder [14] can be found recently. Normally, analytical methods could provide more physical insights into the electromagnetic scattering than numerical methods. Nevertheless, due to the complicate derivations of the analytical methods, so far only simple regular shapes of anisotropic particle were considered. The dyadic Green's function technique (DGF) based on modified vector spherical wave functions (VSWFs) is more flexible and has been widely applied to the radiation and scattering problems [15,16]. Nevertheless, in some applications, such as prediction of radiation pressure and torque exerted on biological organs, obstacles are encountered since it is difficult and lengthy to derive the scattering coefficients of those dyadic Green's functions in analytical and compact form.

As one of the most powerful and effective tools for exactly solving the scattering problem of arbitrary shaped particles, the T-matrix approach has also been used to find solutions for anisotropic particles. Along with the development of T-matrix method, a variety of techniques have been used for constructing the T-matrix formulae, although the extended boundary condition method (EBCM), or the null-field method (NFM) was the most commonly used one [17]. Multiple scattering approach based on the expansion of electromagnetic field in terms of VSWFs was applied to construct T-matrix formulae in handling the electromagnetic scattering by nonspherical anisotropic particles [18–20]. Stout [21,22] gave a numerical algorithm which could be used to generate the T-matrix of an anisotropic sphere with an extension of Mie theory. Kiselev et al. [23] solved the scattering problem of radically and uniformly anisotropic spheres by developing a series of quasi-spherical vector wave functions (qSVWFs) to represent the internal electromagnetic fields.

A similar set of qSVWFs were derived by Doicu [24] by using inverse Fourier transform, and electromagnetic scattering from a uniaxial anisotropic particle was analyzed. Recently this method was extended to the characteristics of biaxial anisotropic particle by Schmidt and Wriedt [25] by developing a set of qSVWFs for biaxial anisotropic media. Furthermore, an attempt to extend the T-matrix approach for a wider range of anisotropic scatterers with arbitrary permittivity tensor could be found in Ref. [26]. Nevertheless, it seems that the extension in Ref. [26] is not in a complete form although it was aimed at treating the most general permittivity tensors. For instance, the special case of gyroelectric anisotropic medium cannot be covered.

In the aim of finding an effective solution for dealing with electromagnetic scattering from nonspherical gyroeletric anisotropic particle, in the present paper, T-matrix formulae are constructed based on the EBCM technique, where a system of qSVWFs for an expansion representation of electromagnetic field inside gyroelectric media is derived, and solutions are presented for the study of interaction between gyroelectric particle and electromagnetic wave.

The remainder of this paper is organized as follows. In Section 2, by using the inverse Fourier transform, a system of qSVWFs is derived for an expansion representation of electromagnetic fields inside gyroelectric anisotropic media. Based on the derived series of qSVWFs, T-matrix formulae are constructed to find solutions to electromagnetic scattering from a gyroelectric anisotropic particle by using the EBCM technique. The verification of theoretical treatments are then made in Section 3 based on a home-made FORTRAN program, numerical results obtained using the presented method are compared with those published data obtained using other methods, and then some representative results are presented to analyze the effect of shape deformation and of anisotropy components upon the scattering properties. Some discussions are presented in Section 4, which also serves as a conclusion.

2. Theoretical treatments

2.1. Expansion of electromagnetic fields in gyroelectric media

To find a solution for the electromagnetic scattering problem in the framework of T-matrix method, an expansion representation of the electromagnetic fields inside the scatterer in terms of vector wave functions is needed. For instance, VSWFs are commonly used in the expansion of electromagnetic fields in isotropic media. To find an expansion representation of electromagnetic fields in the uniaxial anisotropic media, series of quasi-spherical vector wave functions (qSVWFs) were derived by Kiselev et al. [23] and by Doicu [24], respectively. And a series of qSVWFs for the expansion of electromagnetic fields in the biaxial anisotropic media was given by Schmidt and Wriedt [25]. In this section, a series of qSVWFs are derived for the expansion representation of electromagnetic fields inside gyroelectric anisotropic media.

The electromagnetic fields in a homogeneous anisotropic free-source medium can be characterized by the Maxwell equations [27]:

$$\nabla \times \mathbf{E} = ik_0\mathbf{B}, \quad \nabla \times \mathbf{H} = -ik_0\mathbf{D}$$
$$\nabla \cdot \mathbf{B} = 0, \quad \nabla \cdot \mathbf{D} = 0 \tag{1}$$

with constitutive relations

$$\mathbf{D} = \overline{\varepsilon}\mathbf{E} \quad \mathbf{B} = \overline{\mu}\mathbf{H} \tag{2}$$