Lecture Notes in Electrical Engineering 929

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S. P. Singh *Editors*

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Preface

This book contains the proceedings of papers presented in the 1st International Conference on Advances in Signal Processing and Communication Engineering (ICASPACE-21), held in July 2021, in the Department of Electronics and Communication Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, India. The conference invited papers from research scholars, academicians, industry professionals and scientists. It provided them with a platform to discuss and put forward their ideas and research findings with their peers worldwide. Further, ICASPACE-21 organized six invited talks delivered by (i) Dr. N. Sudarshan Rao, Professor, Penn State Behrend, Erie, USA; (ii) Dr. Mahendar Kumbham, Valeo, Ireland Photonics; (iii) Dr. T. G. Thomas, Professor, BITS Pilani, UAE; (iv) Mr. Swapnil Bora, Founder and CEO, MeshTek Labs, Texas, USA; (v) Dr. Yatindra Nath Singh, Professor (HAG), Electrical Engineering Department, IIIT Kanpur, India; and (vi) Dr. Anupam Sharma, Associate Director, DSP, DRDO, Hyderabad, India. This provided an opportunity for the participants to listen to the eminent speakers in the areas of signal processing and communication engineering.

ICASPACE-21 received a total of 220 papers in the areas of signal processing, communication, VLSI, IoT and machine learning applications in these areas, across four countries. Works submitted to the conference underwent a rigorous single-blind peer review each by three experts (among which two are from external Institutions) selected by the conference committee. To ensure a quality review process, each subject expert was not assigned more than five papers. Subsequently, the authors were given an opportunity to incorporate the review comments given by the reviewers. After comprehensive verification of technical content, plagiarism and grammar, the conference committee recommended 44 papers be published in this proceedings book.

This book covers several theoretical and mathematical approaches that address different challenges in signal, image, speech processing and communication systems. It primarily focuses on effective mathematical methods, algorithms and models that enhance the performance of existing systems. The areas include advances in signal processing (radar and biomedical), image processing (satellite, medical and general optical images), speech processing (speech signal compression, conversion and audio mixing). Further, the contents of this book address technical and environmental challenges in 5G technology, strategies for optimal utilization of resources to improve the efficacy of the communication systems in terms of bandwidth and radiating power, some innovative IoT applications, mathematical, theoretical and algorithmic aspects of evolutionary computation models that support hybrid intelligence in machine learning/deep learning problems with applications focused in signal processing; exploratory research in electromagnetics, microwave and radar signal processing.

Through this book, we aim to unify the latest achievements of the authors in the research projects and practices across several areas of signal processing and communication engineering. We further expect this book will act as a catalyst for research in related areas, future collaborations and international cooperation.

We would like to express our appreciation and heartfelt thanks to every individual who has directly or indirectly contributed toward the content quality improvement of this conference proceedings and consistently assisted us in consolidating and bringing the works submitted to the ICASPACE-21 into good shape.

Florence, USA Ravi Paul Gollapalli
Patna, India Pradip Kumar Jain
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About the Editors

Pradip Kumar Jain is a Professor in Electronics Engineering, and he is the Director of the National Institute of Technology Patna. Dr. Jain has immense experience both in research and administration. He made a significant contribution to the analysis, modeling, and development of high-power microwave tubes and gyrotron devices. Prof. Jain guided 20 Doctoral theses and has 100 peer-reviewed articles published in indexed journals, 200 conference proceedings, a patent, and authored six book/monograph chapters, to his credit. He served in various administrative positions as Dean-R&D at IIT (BHU), Varanasi; Coordinator of Microwave Tubes Research Centre and Centre of Advanced Studies; Head of the Department of Electronics Engineering, IIT (BHU). Prof. Jain did extensive R&D activities in collaboration with CEERI (CSIR, Pilani), DRDO, IPR (DAE, Gandhi Nagar), and successfully executed numerous sponsored research projects.

Yatindra Nath Singh is currently the Dean of Infrastructure and Planning at IIT Kanpur. Prof. Singh has led a team of researchers and academicians across India to develop Brihaspati, a project that aims at developing a platform-independent highly scalable content delivery system for a web-based e-learning system. He pursued his under graduation in electrical engineering from REC Hamirpur (present National Institute of Technology Hamirpur), a master's with a specialization in optoelectronics and optical communications, and a Ph.D. in optical communication networks from IIT Delhi. He supervised 15 Ph.D. theses, published several journal articles, and conference proceedings, and completed several sponsored projects besides Brihaspati.

Ravi Paul Gollapalli is an Associate Professor in the Department of Engineering Technology at the University of North Alabama. He has an electrical engineering background with a specialization in optics and has research experience in signal and image processing, pattern recognition analysis for remote sensing, and applications of femtosecond lasers. Dr. Gollapalli received his Ph.D. from the University of Alabama, Huntsville, and was a Post-Doctoral Research Associate at the University of South Alabama, USA. He has published his works in peer-reviewed Journals, Conferences, and a book chapter. Besides, Dr. Gollapalli is actively involved in experimental works, numerical simulations, simulation of femtosecond laser pulse propagation in materials, fabrication of nanostructures on glass and silicon substrates using micro/nanofabrication processes, and designing RF circuits for noise analysis. Further, he built an optical amplifier (EDFA) and supported the processing of signals from an impedance probe equipped on-board the NASA SOUND rocket.

S. P. Singh is a Professor and Head of the Electronics and Communication Engineering Department at Mahatma Gandhi Institute of Technology, Hyderabad. He worked for 18 years in the Indian Army Corps of EME. During his service in the Indian Army, he was in radar maintenance activities. Dr. Singh has developed a synchro-based training model for defense application, received several cash rewards for his indigenization work on the radar Schilka and did several modifications in radar SFM to reduce the error rate. Later he chose his career as an academician. Dr. Singh received his Ph.D. from Osmania University, Hyderabad, in 2007. He supervised three doctoral theses so far, and four are in progress. He has over 96 publications in journals and conference proceedings and completed several funded projects from AICTE.

Lumped Circuit Modeling at Nanoscale (Part-I: Dielectric Anisotropy)

Sudarshan R. Nelatury

Abstract The past decade has witnessed a growing interest in pushing the limits of lumped circuit theory to the analysis and design of nanocircuits at infrared and visible frequencies. Just as how a relentless pursuit of microminiaturization of electronic devices has resulted in the very large-scale integration (VLSI) technology today, an even more aggressive research activity in the field of metamaterials and complex media opened roadmaps for subwavelength nanostructures. The motive for this urge is to break free from the diffraction limit and pitch into all new frontiers of plasmonics and nano-technology, whereby information processing and transmission are projected to happen at a greater speed and lower power levels. In order for nanocircuits and systems to develop, it is imperative that electromagnetic interaction with nanoparticles made of diverse media types be studied not only using full wave analysis, but also with the aid of quasi-static approach. Numerous papers have appeared that considered dielectric and plasmonic particles possessing isotropy, but dielectric anisotropy and bianisotropy have yet to garner their rightful attention. This paper aims to carry out this in case of anisotropic nanospheres. In a companion paper, we shall consider the equivalent circuits of nanospheres. We shall outline quasi-static analysis and derive fields both inside and outside a nanosphere and obtain equivalent circuit that takes into account coupling between two nanospheres.

Keywords Anisotropic medium · Nanocircuits · Quasi-static model · Lumped circuits

1 Introduction

With growing demand for nanomaterials and nanocircuitry, there is a greater need to characterize complex material media and nanoparticles and develop equivalent circuits that serve as reasonably accurate models as far as terminal behavior is con-

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cerned. If the size of a nanoparticle is too small, quantum effects play their role, but if it is small enough at optical and infrared wavelengths to render quasi-static analysis applicable, it is possible to develop a lumped circuit model for these particles. Today, the traditional techniques that were prevalent at microwave and millimeter wave are being scaled down to optical systems. Examples include lidar for detection of stationary or moving objects submerged under water, measurement of turbulence in airways and malignant tumors in biological tissues. Optical signals modulated at few GHz of frequencies as in lidar–radar promise superior performance in many ways compared to lidar. Examples of research works are, for instance [1], surfaces in the design and development of very complex tunable high-speed laser for frequency-chirped lidar–radar systems and other sophisticated applications.

Optical nanocircuits at subwavelength operations are being devised at a faster pace without the aid of mechanical steering, but solely incorporating electrical tuning. Typical functions include coupling mechanisms of various kinds, splitting and redirecting of power and so on [2].

We know that scattering from conducting spheres and multiply stratified media can be formulated and solved using the Mie formulation [3], which lays down a strong mathematical basis. Several authors succeeded in the use of full-wave analysis to determine scattering in case of a general anisotropic sphere possessing a radius of arbitrary magnitude. Although their work is quite exact, it is too rigorous to be understood by a common designer. There are quite a few numerical software tools commercially available; they prove to be an overkill for the simple object of circuit modeling or elucidating the terminal characteristics that reasonably represent interaction between an em wave and a nanoparticle. Expediency calls for simple closed-form expressions in terms of integrated quantities like terminal voltages and currents.

A quasi-static approach may well be adopted in case of a nanoparticle whose physical presence occupies smaller space compared to the wavelength of operation. Solution of Maxwell field equations, which in general is more complicated could be held in abeyance, and one might employ the stopgap of the lumped circuit theory [4]. The more exact solution involves dipole moments of higher order. But if we ignore all of them and pick just the dominant single dipole term, the resulting expressions have an accuracy that would be acceptable for majority of scenarios and applications. It permits lumped circuit formulation.

In this paper, we shall present the quasi-static field analysis considering an *anisotropic* dielectric particle in the form of a sphere of small radius. It is assumed that the sphere is exposed to a plane electromagnetic wave. First, we shall set up field vectors both inside and outside the sphere. The average effects of these fields obtained by integration from the bottom pole to the top pole of the nanosphere and also around the horizontal section of the sphere are used in defining terminal voltages and currents. These expressions constitute the basis for circuit modeling of nanospheres [4, 5].

When a dielectric nanosphere is illuminated by an incoming wave, dipole formation occurs described as dielectric polarization. It is reasonable to assume that the electric field inside the sphere is almost invariant and may be viewed as the field averaged over the volume and arising from the bound charge inside the sphere. As for the region outside the sphere, in addition to the incident field, we might consider the bound charge as a single dipole placed at the center, and the field resulting from this can be added to the former.

The average dipole moment per unit volume determines the average induced field strength inside. The field of the incident uniform plane wave brings about almost constant polarization whose density might be assumed to arise from its dyadic transformation. Imposition of boundary conditions permits the determination of this dyadic. This transformation dyadic after all the mathematical simplification appears to be a straightforward generalization of the scalar value it has in case of a simple isotropic sphere.

Two simple numerical examples are included showing the angle of refraction suffered by the electric field vector. Assuming that the particle is made of a gyrotropic material in a static magnetic field, angles of refraction of field vector in the particle are shown to vary with the angle made by the magnetic field with the incident electric field vector. Just as how an isotropic nanosphere acts as a fixed resistor–capacitor or resistor–inductor nanocircuit depending on whether it is non-plasmonic or plasmonic [4, 5], an anisotropic nanosphere can be used to realize a multi-port or tunable circuit element [6, 7].

As for the notation, we shall employ an overbar to denote a vector, a hat for a unit vector, a double overbar to denote a dyadic and the identity dyadic by $\overline{\overline{I}}$.

2 Dielectric Anisotropy

Before we obtain expressions for the fields in case of a nanoparticle, let us provide a brief overview of dielectric anisotropy. This helps the reader to gain some physical insights. The constitutive properties of an isotropic medium do not depend on spatial direction, but that of an anisotropic medium do. In an isotropic medium, the electric flux density vector and the field intensity vector and, likewise, the magnetic flux density vector and magnetic field intensity are co-directional. On the other hand, there is an angle between these pairs of vectors in an anisotropic medium. Accordingly, their Cartesian components are related by dyadics. The Tellegen constitutive relations for an anisotropic medium are

$$\overline{D} = \overline{\overline{\epsilon}} \cdot \overline{E} \tag{1}$$

$$\overline{B} = \overline{\overline{\mu}} \cdot \overline{H} \tag{2}$$

In this work, let us consider only electric anisotropy and assume that $\overline{\overline{\mu}} = \mu\, \overline{\overline{I}}$. Dielectric anisotropy arises naturally on account of crystalline structure of materials, and depending on the values of the elements of the permittivity tensor $\overline{\overline{\epsilon}}$, it is said to be one of the hexagonal, isotropic, monoclinic, orthorhombic, tetragonal, triclinic, trigonal systems [8–10]. The global properties of a materials can be represented in terms of the local properties with the aid of rotation dyadics. The permittivity dyadic has a general form given by

$$\overline{\overline{\epsilon}} = \epsilon_0 \, \overline{\overline{\mathcal{R}}} \cdot \left(\epsilon_a \hat{x}\hat{x} + \epsilon_b \hat{y}\hat{y} + \epsilon_c \hat{z}\hat{z}\right) \cdot \overline{\overline{\mathcal{R}}}^{\,T} \tag{3}$$

where the superscript T stands for transpose and

$$\overline{\overline{\mathcal{R}}} = \overline{\overline{\mathcal{R}}}_x \cdot \overline{\overline{\mathcal{R}}}_y \cdot \overline{\overline{\mathcal{R}}}_z \tag{4}$$

$$\overline{\overline{\mathcal{R}}}_u = \left(\overline{\overline{I}} - \hat{u}\hat{u}\right)\cos(\theta_u) + \hat{u} \times \overline{\overline{I}}\,\sin(\theta_u) + \hat{u}\hat{u} \tag{5}$$

$$\text{for}\, u = x, y, z.$$

In the general case when $\epsilon_a \neq \epsilon_b \neq \epsilon_c$, $\overline{\overline{\epsilon}}$ is said to be biaxial. If $\epsilon_a = \epsilon_b$, it is uniaxial. A special case of anisotropy arises when the permittivity dyadic is uniaxial and also has an antisymmetric part. Such materials are said to be gyrotropic. Examples of gyrotropic media include ferrites such as Yttrium iron garnet (YIG) with chemical composition $Y_3Fe_2(FeO_4)_3$ or $Y_3Fe_5O_{12}$ [11] and magnetized plasmas [12]. In an unmagnetized plasma, the permittivity as a function of frequency is given by [10]

$$\epsilon(\omega) = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega(\omega - i\nu_c)}\right) \tag{6}$$

where $\omega_p = e\sqrt{\frac{n}{m\epsilon_0}}$ is the plasma frequency related to the electron charge e, mass m and the electron density n. The collision parameter ν_c arises due to damping and takes into account losses in the medium. If the average electron density is sparse, this number can be neglected. Suppose the plasma is subjected to a steady biasing magnetic field $\overline{B} = B\,\hat{g}$, the electrons suffer Lorentz force and begin to rotate about the magnetic field vector. The plasma then becomes uniaxial and nonreciprocal with antisymmetric components manifesting themselves. The permittivity dyad can be represented as:

$$\overline{\overline{\epsilon}} = \epsilon_0 \left(\epsilon_a\,\hat{g}\hat{g} + \epsilon_t\,(\overline{\overline{I}} - \hat{g}\hat{g}) - i\delta\,\hat{g} \times \overline{\overline{I}}\right). \tag{7}$$

where ϵ_a has the same expression as in (6) but ϵ_t and δ are now given by

$$\epsilon_t(\omega) = \epsilon_0 \left(1 - \frac{(\omega/\omega_p)^2\,[1 + i\nu_c/\omega]}{[1 + i\nu_c/\omega]^2 - (\omega_b/\omega)^2}\right) \tag{8}$$

$$\delta = \epsilon_0 \left(\frac{(\omega/\omega_p)^2\,(\omega_b/\omega)}{[1 + i\nu_c/\omega]^2 - (\omega_b/\omega)^2}\right) \tag{9}$$

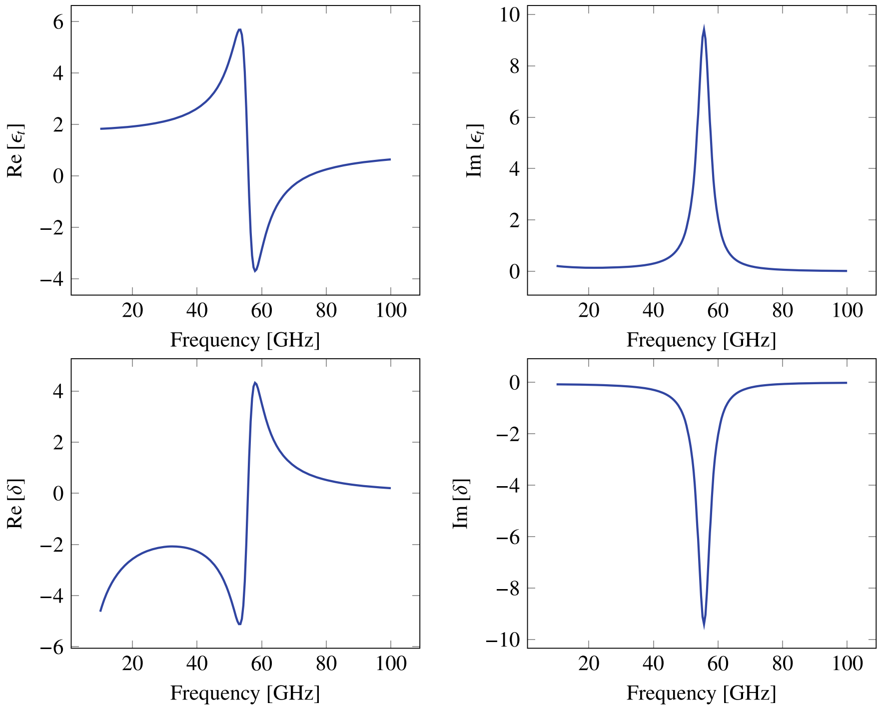

Fig. 1 Real and imaginary parts of ϵ_t and δ for $\omega_p = 2\pi \times 50 \times 10^9$ rad/s, $\omega_b = 3.5 \times 10^{11}$ rad/s, $\nu_c = 1.5 \times 10^{10}$

where $\omega_b = eB/m$, called the gyrofrequency. To illustrate the dispersive characteristics of elements of the permittivity dyadic, suppose we take the typical values: $\omega_p = 2\pi \times 50 \times 10^9$ rad/s, $\omega_b = 3.5 \times 10^{11}$rad/s, $\nu_c = 1.5 \times 10^{10}$ and plot the real and imaginary parts of ϵ_t and δ, they appear to vary as shown in Fig. 1. Electromagnetic interaction of anisotropic nanoparticles at optical frequencies permits us to take lumped circuit theory to a whole new realm. Tunable circuit elements using gyrotropic particles was reported in [6]. In [13], we shall attempt to extend the ideas in [6] to general anisotropic dielectrics and show how coupling between two particles can be characterized.

3 Fields Internal and External to the Sphere

This section is adapted from the author's previous work [7]. Consider a nanosphere of radius R placed in free space with origin of coordinates at its center as shown in Fig. 2. Assume that the particle is illuminated by a time harmonic wave ($e^{-i\omega t}$ notation) with the electric field $\overline{E}_{\text{inc}} = \overline{E}_0 = E_0\,\hat{z}$. Let the permittivity and permeability tensors of

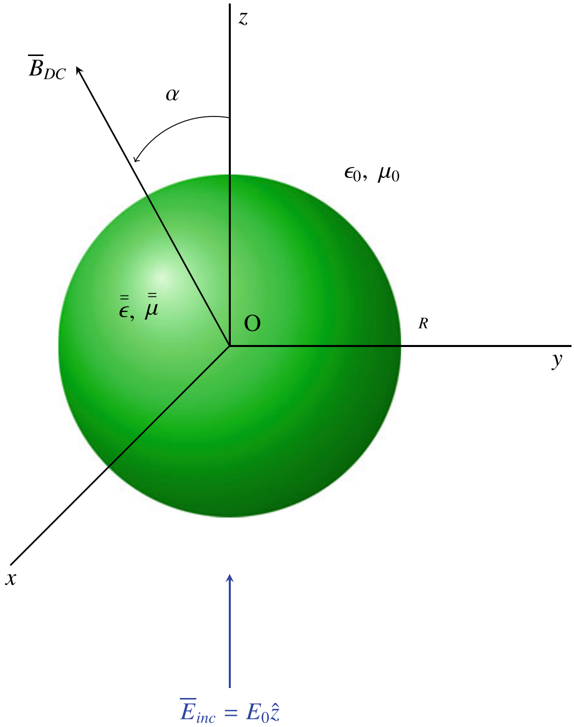

Fig. 2 Anisotropic nanoparticle exposed to an incident wave $\overline{E}_{\text{inc}} = E_0\hat{z}$. R is the radius of the sphere. Medium parameters of the sphere are shown as dyadics. The static magnetic field imparts gyroelectric behavior to the particle, and by varying the orientation angle α, the medium parameters can be varied

the particle be $\overline{\overline{\epsilon}}$ and $\overline{\overline{\mu}}$, respectively. As mentioned before, let us assume that $\overline{\overline{\mu}} = \mu\ \overline{\overline{I}}$. As a special case, the anisotropy might arise due to the gyrotropic characteristic of the nanosphere in the presence of a static magnetic field of density $\overline{B}$ shown in Fig. 2 oriented at an elevation angle α.

The incident field causes dielectric polarization in the sphere. Let the polarization vector be $\overline{P}$. This is directly proportional to $\overline{E}_0$, and we can use a scalar to represent the proportionality in case of an isotropic medium. But in an anisotropic medium, we are required to have a tensor. So for convenience, let

$$\overline{P} = 3\epsilon_0\ \overline{\overline{\gamma}}\ \cdot \overline{E}_0. \tag{10}$$

where $\overline{\overline{\gamma}}$ is as yet unknown. If the volume of the sphere is $\tau = \frac{4}{3}\pi R^3$, the average dipole moment acting in the sphere is

$$\overline{p} = \tau \overline{P} \tag{11}$$

$$= 3\epsilon_0\, \tau\ \overline{\overline{\gamma}}\ \cdot \overline{E}_0 \tag{12}$$

$$= 4\pi\epsilon_0 R^3\ \overline{\overline{\gamma}}\ \cdot \overline{E}_0. \tag{13}$$

The electric field due to the dielectric polarization, averaged over the volume inside the sphere, can be obtained using the quasi-static model as long as the size of the nanosphere is smaller than the wavelength. Our derivation follows the analysis in [14] for an isotropic sphere, but considerably differs in the sense that we are considering an *anisotropic* sphere in this paper.

Let $\Phi(\overline{r})$ be the quasi-electrostatic potential arising due to a charge distribution $\rho(\overline{r'})$ given by

$$\Phi(\overline{r}) = \frac{1}{4\pi\epsilon_0} \iiint\limits_{0<r'<R} \frac{\rho(\overline{r'})\,\mathrm{d}v'}{|\overline{r}-\overline{r}'|}. \tag{14}$$

The volume averaged electric field due to the dielectric polarization $\overline{E}_P$ is

$$\overline{E}_P = \frac{1}{\tau} \iiint\limits_{0<r<R} -\nabla\Phi(\,\overline{r}\,)\,\mathrm{d}v \tag{15}$$

$$= \frac{-1}{\tau} \oint\!\!\oint\limits_{r=R} R^2\Phi(\,\overline{r}\,)\,\hat{r}\,\mathrm{d}\Omega \tag{16}$$

$$= \frac{-R^2}{4\pi\epsilon_0\tau} \iiint\limits_{0<r'<R} \rho(\overline{r'})\,\mathrm{d}v' \oint\!\!\oint\limits_{r=R} \frac{\hat{r}\,\mathrm{d}\Omega}{|\overline{r}-\overline{r}'|} \tag{17}$$

where $\mathrm{d}v$ and $\mathrm{d}\Omega$ denote differential volume and differential solid angle, respectively. In the case of a sphere, there exists azimuthal symmetry, and the reciprocal distance in (17) can be expressed as

$$\frac{1}{|\overline{r}-\overline{r}'|} = \sum_{\ell=0}^{\infty} \frac{r_<^{\ell}}{r_>^{1+\ell}} P_\ell\left(\hat{r}\cdot\hat{r}'\right) \tag{18}$$

$$= 4\pi \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \frac{1}{2\ell+1} \frac{r_<^{\ell}}{r_>^{1+\ell}} Y_{\ell m}^*(\theta',\phi') Y_{\ell m}(\theta,\phi) \tag{19}$$

where $P_\ell(\cdot)$ is the Legendre polynomial of order ℓ, $Y_{\ell m}(\theta,\phi)$ are spherical harmonics, $r_<$ is smaller of r and r' and likewise $r_>$ is the greater of them. When the surface integral in (17) is taken over the surface of the sphere, $r_< = r'$ and $r_> = R$. Further, expanding $\hat{r}$ in rectangular components, we observe that orthogonality strikes off all the terms in the summation of (18) except the one corresponding to $\ell = 1$. This permits us to rewrite (17) as

$$\overline{E}_P = \frac{-R^2}{4\pi\epsilon_0\tau} \iiint\limits_{0<r'<R} \rho(\overline{r'})\,\mathrm{d}v' \oint\!\!\oint\limits_{r=R} \frac{r'}{R^2}\,\overline{\overline{R}}\cdot\hat{r}'\,\mathrm{d}\Omega \tag{20}$$

where $\overline{\overline{R}} = \hat{r}\hat{r}$. Also, since

$$\oiint_{r=R} r' \,\overline{\overline{R}} \cdot \hat{r}' \, d\Omega = \frac{4\pi}{3} \overline{r}' \tag{21}$$

we can modify (20) as

$$\overline{E}_P = \frac{-1}{3\epsilon_0 \tau} \iiint_{0<r'<R} \overline{r}' \rho(\overline{r'}) \, dv' \tag{22}$$

$$= -\frac{1}{3\epsilon_0} \overline{P} \tag{23}$$

$$= -\overline{\overline{\gamma}} \cdot \overline{E}_0. \tag{24}$$

The polarization as seen from outside the sphere seems as if it were the field of a dipole, which from (13) is given by

$$\overline{E}_{\text{dip}} = \frac{3\,\overline{\overline{R}} \cdot \overline{p} - \overline{p}}{4\pi\epsilon_0 r^3} \tag{25}$$

$$= \left(3\,\overline{\overline{R}} \cdot \overline{\overline{\gamma}} \cdot \overline{E}_0 - \overline{\overline{\gamma}} \cdot \overline{E}_0\right) \frac{R^3}{r^3}. \tag{26}$$

So now the total fields internal and external to the sphere are given by

$$\overline{E}_{\text{int}} = \overline{E}_0 + \overline{E}_P \tag{27}$$

$$= \overline{E}_0 - \overline{\overline{\gamma}} \cdot \overline{E}_0 \tag{28}$$

$$\overline{E}_{\text{ext}} = \overline{E}_0 + \left(3\,\overline{\overline{R}} \cdot \overline{\overline{\gamma}} \cdot \overline{E}_0 - \overline{\overline{\gamma}} \cdot \overline{E}_0\right) \frac{R^3}{r^3}. \tag{29}$$

We can find $\overline{\overline{\gamma}}$ using the boundary conditions. One might verify that the tangential component in the $\hat{\theta}$ direction is satisfied independent of $\overline{\overline{\gamma}}$, but in order to meet the boundary condition on the normal component of the electric displacement density in the $\hat{r}$ direction we require that

$$\hat{r} \cdot \overline{\overline{\epsilon}} \cdot \overline{E}_{\text{int}}\Big|_{r=R} = \hat{r} \cdot \epsilon_0 \,\overline{\overline{I}} \cdot \overline{E}_{\text{ext}}\Big|_{r=R} \tag{30}$$

where $\overline{\overline{I}}$ stands for the identity dyadic as mentioned at first. Using (28) and (29),

$$\hat{r} \cdot \overline{\overline{\epsilon}} \cdot \left(\overline{E}_0 - \overline{\overline{\gamma}} \cdot \overline{E}_0\right) = \hat{r} \cdot \epsilon_0 \left(\overline{\overline{I}} + 3\,\overline{\overline{R}} \cdot \overline{\overline{\gamma}} - \overline{\overline{\gamma}}\right) \cdot \overline{E}_0 \tag{31}$$

$$= \hat{r} \cdot \left(\epsilon_0 \,\overline{\overline{I}} + 2\epsilon_0 \,\overline{\overline{I}} \cdot \overline{\overline{\gamma}}\right) \cdot \overline{E}_0 \tag{32}$$

and rearranging terms,

$$\hat{r}\cdot\left\{(\overline{\overline{\epsilon}}-\epsilon_0\,\overline{\overline{I}})-(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\cdot\overline{\overline{\gamma}}\right\}\cdot\overline{E}_0=0. \tag{33}$$

In the above, $\hat{r}$ can be anywhere on the sphere and is arbitrary whereas, $\overline{E}_0$ is impressed from outside and does not depend on the medium. So it requires that

$$(\overline{\overline{\epsilon}}-\epsilon_0\,\overline{\overline{I}})-(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\cdot\overline{\overline{\gamma}}=\overline{\overline{\emptyset}} \tag{34}$$

or

$$\overline{\overline{\gamma}}=(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})^{-1}\cdot(\overline{\overline{\epsilon}}-\epsilon_0\,\overline{\overline{I}}) \tag{35}$$

where $\overline{\overline{\emptyset}}$, needless to say, is the null dyadic. This is the *generalized Clausius–Mossotti transformation dyadic.* Next using the identity

$$\left(\overline{\overline{A}}+\alpha\,\overline{\overline{I}}\right)^{-1}\equiv\left(\alpha^2\,\overline{\overline{I}}+\alpha(\overline{\overline{A}}_{\mathrm{t}}\overline{\overline{I}}-\overline{\overline{A}})+\operatorname{adj}\overline{\overline{A}}\right)/|\,\overline{\overline{A}}\,| \tag{36}$$

where the subscript t stands for the trace, one might readily verify that the members taking part in the dot product in (35) commute, so we might as well write equivalently,

$$\overline{\overline{\gamma}}=(\overline{\overline{\epsilon}}-\epsilon_0\,\overline{\overline{I}})\cdot(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})^{-1} \tag{37}$$

Equations (35) and (37) were earlier derived in another excellent paper [15] starting from Hall effect in an alternative manner. They can be equivalently expressed in terms of double products [16] as,

$$\overline{\overline{\gamma}}=\frac{3(\overline{\overline{\epsilon}}-\epsilon_0\,\overline{\overline{I}})\cdot\left((\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\overset{\times}{\times}(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\right)^T}{\left((\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\overset{\times}{\times}(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})\right):(\overline{\overline{\epsilon}}+2\epsilon_0\,\overline{\overline{I}})} \tag{38}$$

where the superscript T denotes transpose. The symbols : and $\overset{\times}{\times}$ stand for double dot and double crossproducts respectively. For the dyads $\overline{p}\,\overline{q}$ and $\overline{r}\,\overline{s}$, they can be written [16, 17] as

$$\overline{p}\,\overline{q}:\overline{r}\,\overline{s}=(\overline{p}\cdot\overline{r})(\overline{q}\cdot\overline{s}) \tag{39}$$

$$\overline{p}\,\overline{q}\overset{\times}{\times}\overline{r}\,\overline{s}=(\overline{p}\times\overline{r})(\overline{q}\times\overline{s}) \tag{40}$$

$$\begin{aligned}&=(\overline{p}\times\overline{r})\cdot(\overline{q}\times\overline{s})\,\overline{\overline{I}}+(\overline{p}\cdot\overline{s})\overline{q}\,\overline{r}+(\overline{r}\cdot\overline{q})\overline{s}\,\overline{p}\\&\quad-(\overline{p}\cdot\overline{q})\overline{s}\,\overline{r}-(\overline{r}\cdot\overline{s})\overline{q}\,\overline{p}\end{aligned} \tag{41}$$

Substituting (35) or (37) in (28) and (29), we can obtain the quasi-static electric fields internal and external to the sphere. When specialized to ordinary isotropic case, all the expressions derived so far tally with those found in [14]. The associated magnetic fields can be found in a like manner. Suppose the sphere is magnetically isotropic with a permeability μ, in the present $\mathrm{e}^{-i\omega t}$ notation, the magnetic fields are given by

$$\overline{H}_{\text{int}} = \frac{1}{i\omega}\mu^{-1} \cdot \nabla \times \overline{E}_{\text{int}} \tag{42}$$

$$\overline{H}_{\text{ext}} = \frac{1}{i\omega}\mu_0^{-1}\ \nabla \times \overline{E}_{\text{ext}}. \tag{43}$$

4 Angle(s) of Refraction

Now, we shall find the angle between the incident electric field $\overline{E}_{\text{inc}}$ and the field vector inside the sphere $\overline{E}_{\text{int}}$. The incident electric field vector $\overline{E}_{\text{inc}}$ is in the $\hat{z}$ direction. Let the orientation of the field internal to the sphere be given in spherical coordinate system by the elevation and azimuthal angles (ϑ, φ). Using Eq. (28), we can find these angles as

$$\vartheta = \cos^{-1}\left\{\frac{1-\gamma_{zz}}{\sqrt{\gamma_{xz}^2+\gamma_{yz}^2+(1-\gamma_{zz})^2}}\right\} \tag{44}$$

$$\varphi = \tan^{-1}\left(\frac{\gamma_{yz}}{\gamma_{xz}}\right). \tag{45}$$

Next, we shall offer two simple numerical examples. The permeability is assumed to be μ_0 and the magnetic fields are not computed.

5 Numerical Examples

Example 1 Suppose the nanosphere is made of an anisotropic material whose permittivity dyadic has a general form given by (3)–(5). For the choice of values $\epsilon_a = 6$, $\epsilon_b = 4$, $\epsilon_c = 2$, $\theta_x = 60°$, $\theta_y = 30°$,, $\theta_z = 45°$, we get $\vartheta = 13.52°$ and $\varphi = -4.1°$. This choice is arbitrary and is meant to provide a numerical example. A yttrium iron garnet (YIG)-based particle has been used to realize a tunable lumped circuit element, and the variation of capacitance was reported by the author in [6].

Example 2 For a second example, let us consider a nanosphere made of gyroelectric material biased with a static magnetic field of flux density $\overline{B}_{DC} = B_{DC}\,\hat{g}$, where α