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ELECTROMAGNETIC SCATTERING FROM INHOMOGENEOUS OBJECTS EMBEDDED IN SPHERICALLY MULTILAYERED MEDIA SOLVED BY THE METHOD OF MOMENTS

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ABSTRACT: *The method of moments (MOM) is applied to solve electromagnetic (EM) scattering problems in spherically multilayered media. A spectral-domain dyadic Green's function (DGF) in a spherically multilayered medium is constructed in terms of the spherical vector wave functions by using the method of scattering superposition in the spherical coordinate system. Its expression is later transformed to that in the Cartesian coordinate. We discretize the computational domain which contains the scatterer into N size-independent cells in the Cartesian coordinate. Based on the transformed DGFs, the volume integral equations can be solved by MOM combined with Krylov subspace iterative methods. In this letter, we choose the bi-conjugate gradient stabilized (BCGS) iteration method due to its fast convergence. Numerical results compared with FDTD solutions from a commercial software are presented to validate the accuracy and efficiency of our method.* © 2017 Wiley Periodicals, Inc. Microwave Opt Technol Lett 59:526–530, 2017; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.30335

Key words: *method of moments; bi-conjugate gradient stabilized algorithm; spherically layered media; volume integral equation*

1. INTRODUCTION

Electromagnetic (EM) scattering problems in spherically multilayered media are important for many applications, such as geophysics exploring, microwave imaging, target identification and nondestructive testing. The method of moments (MOM) [1,2] is widely used to solve EM scattering problems and has been successfully applied for planarly layered background media [3]. The dyadic Green's function (DGF) is the kernel part of the MOM. Previously, intensive investigations [4–8] have been done to obtain a closed form DGF for spherically multilayered media. However, scattering problems from inhomogeneous objects of arbitrary shapes embedded in a general spherically multilayered medium are scarce in spite of their wide applications. The purpose of this letter is to develop an efficient solution for EM scattering from inhomogeneous objects in a general spherically multilayered medium. The DGF in a spherically layered medium is constructed in terms of the spherical vector wave functions [4,5] by using the superposition in the spherical coordinate system. The non-converging phenomenon of the DGF is eliminated by replacing the series formulation with an analytic form of the unbounded DGF [8]. The expression of the DGF in the spherical coordinate is later transformed to its expression in the Cartesian coordinate. With this transformed DGF for the spherically multilayered media, the scattering problems formulated by the volume electric field integral equation (EFIE) in the Cartesian coordinate can be solved through using MOM.

The EFIE is discretized into a linear system with a number of unknowns by employing the MOM. Krylov subspace iterative methods are applied to replace the direct matrix inverse which normally has a high computation cost. In our work, we use the Bi-Conjugate Gradient Stabilized (BCGS) iteration method to solve the linear system. The BCGS method, presented in Ref. [9] for matrix equations, converges faster than the Conjugate Gradient (CG) [10] method, and smoother than the Bi-Conjugate Gradient (BiCG) method [11].

The method we proposed here can compute the EM scattering from inhomogeneous objects of arbitrary shapes entirely embedded in any layer of a spherically multilayered medium which can have an arbitrary number of layers. In this letter, we use a simple case to validate our method. We assume the scatterer is a homogeneous cube and is buried in the middle layer of a three spherically layered medium which has distinct permittivity, permeability and conductivity of each layer. The BCGS iteration method is chosen to solve the EFIE. The solved total electric fields inside the computational domain and the scattered fields in the outmost layer are compared with the FDTD solutions from a commercial software to validate the accuracy and efficiency of our solver.

2. FORMULATION

The geometry of the EM scattering problem is illustrated in Figure 1, where an inhomogeneous dielectric object of arbitrary shape is completely buried in a spherically multilayered medium that has m layers, each of which has distinct permittivity, conductivity, and permeability $(\varepsilon_i, \mu_i, \sigma_i)$. The complex permittivity is defined as $\bar{\varepsilon}_i = \varepsilon_i + \sigma_i / j\omega$. There is no restriction on the number of the background layers. The impressed sources and receivers can distribute all over the space. In this letter, we consider the condition that the impressed sources are located in the outermost layer (extending to unbounded). The objective of this work is to solve the scattering problems due to a delta electric dipole in spherically layered media. We assume that the scatterer is contained in a rectangular domain in the ith layer denoted by D.

2.1. Volume Electric Field Integral Equation

As shown in Figure 1, in a spherically multilayered medium, an inhomogeneous dielectric scatterer of arbitrary shape is entirely buried in the ith layer. The scattered field $\mathbf{E}^{scat}(\mathbf{r})$ is the difference between the total electric field $\mathbf{E}^{tot}(\mathbf{r})$ and the incident field $\mathbf{E}^{inc}(\mathbf{r})$, or

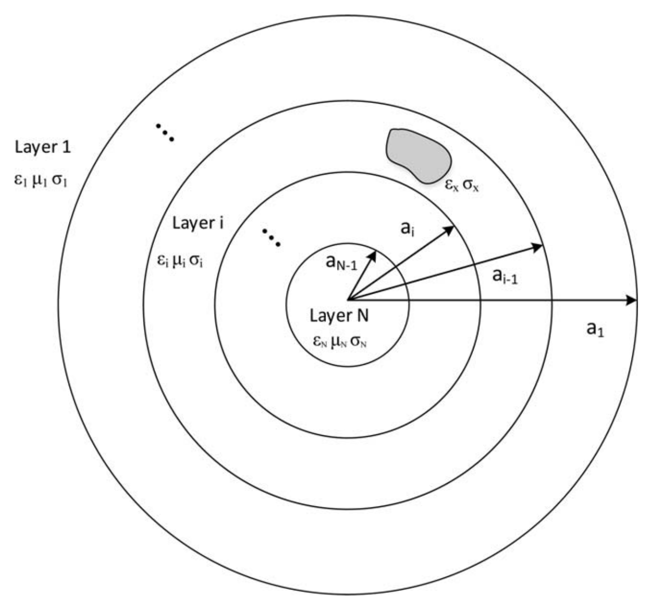

Figure 1 An inhomogeneous object of arbitrary shape buried in a spherically multilayered medium

$$\mathbf{E}^{\text{scat}}(\mathbf{r})=\mathbf{E}^{\text{tot}}(\mathbf{r})-\mathbf{E}^{\text{inc}}(\mathbf{r}) \tag{1}$$

where $\mathbf{r}$ is the position vector in the three dimensional space, and $\mathbf{E}^{\text{inc}}(\mathbf{r})$ is the electric field in the absence of the scatterer but with the presence of the spherically layered background.

The scattered field Escat(R) satisfies the following equation

$$\mathbf{E}^{\text{scat}}(\mathbf{r})=\iiint_{V_D}\overline{\mathbf{G}}_{\text{EJ}}(\mathbf{r},\mathbf{r}')\cdot\mathbf{J}_{\text{eq}}(\mathbf{r}')d\mathbf{r}' \tag{2}$$

where the tensor $\bar{\boldsymbol{G}}_{EJ}(\mathbf{r},\mathbf{r}')$ represents the electrical field DGF in the position of $\mathbf{r}$ due to the electric dipole in the position of $\mathbf{r}'$. According to the volume equivalence theorem, the volume equivalent sources $\mathbf{J}_{\text{eq}}(\mathbf{r}')$ inside the D domain is proportional to the total electric field, or

$$\mathbf{J}_{eq}(\mathbf{r}')=\text{j}\omega\varepsilon_b\chi_\varepsilon(\mathbf{r}')\mathbf{E}^{\text{tot}}(\mathbf{r}') \tag{3}$$

where $\chi_\varepsilon(\boldsymbol{r}')=(\varepsilon(\boldsymbol{r}')-\varepsilon_b(\boldsymbol{r}'))/\varepsilon_b(\boldsymbol{r}'))$ denotes the permittivity contrast, and the subscript b represents the background parameters in the absence of the scatterer. It is obvious that the volume equivalent electric sources are nonzero only inside the scatterer. Thus, the Eqs. (1) and (2) can be rewritten as

$$\mathbf{E}^{\text{inc}}(\mathbf{r})=\mathbf{E}^{\text{tot}}(\mathbf{r})-j\omega\varepsilon_b\iiint_{V_D}\overline{\mathbf{G}}_{\text{EJ}}(\mathbf{r},\mathbf{r}')\cdot\chi_\varepsilon(\mathbf{r}')\mathbf{E}^{\text{tot}}(\mathbf{r}')d\mathbf{r}' \tag{4}$$

Total fields can be obtained by solving the integral equation above as long as the DGF is acquired.

2.2. General Expression of Electrical Dyadic Green's Function

To obtain the electrical DGF in spherically multilayered media, two methods are usually applied for the mathematical derivations. One is to construct the DGF using coordinate tensors [12] while the other is represented by the vector wave functions [4,5]. According to Li's previous work [4,5], the electrical DGF for spherically multilayered media can be written as

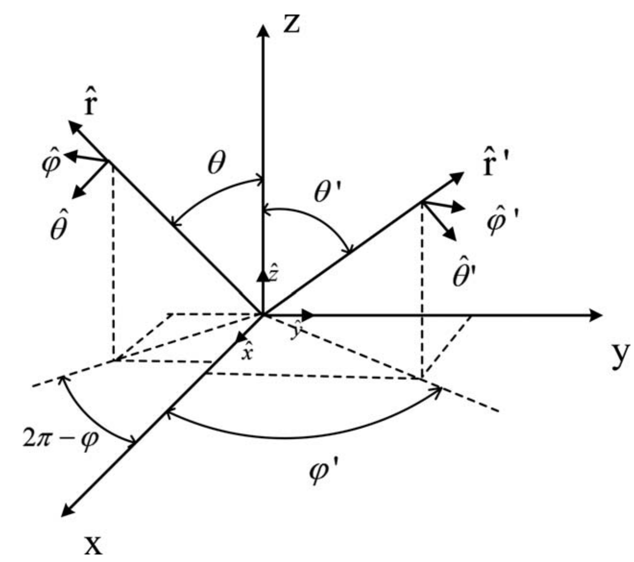

Figure 2 The Cartesian coordinate system and the spherical coordinate systems used in observations and sources points

$$\overline{\mathbf{G}}_{\text{e}}^{\text{fs}}(\mathbf{r},\mathbf{r}')=\overline{\mathbf{G}}_{0e}(\mathbf{r},\mathbf{r}')\delta_{\text{f}}^{\text{s}}+\overline{\mathbf{G}}_{\text{es}}^{\text{fs}}(\mathbf{r},\mathbf{r}') \tag{5}$$

where $\boldsymbol{\delta}_{\text{f}}^{\text{s}}$ denotes the kronecker delta, the unbounded $\bar{\mathbf{G}}_{\mathbf{0e}}(\mathbf{r},\mathbf{r}')$ represents the contribution of the direct waves from electric dipole, while the scattering $\bar{\mathbf{G}}_{\mathbf{es}}^{\mathbf{fs}}(\mathbf{r},\mathbf{r}')$ depicts an additional contribution of multiple reflected and transmitted waves in various layers. The subscript f and the superscript s denote the layers where the field vector position $\mathbf{r}$ and the source vector position $\mathbf{r}'$ are located, respectively. The mathematical expressions of the $\bar{\mathbf{G}}_{\text{e}}^{\text{fs}}(\mathbf{r},\mathbf{r}')$ can be found in Ref. [4]. However, this DGF is not convergent when $\mathbf{r}=\mathbf{r}'$. This problem is solved by replacing the series formulation with an analytic form of the unbounded DGF [8]. In this way, the scattered field in any position can be computed using Eq. (2), even when the equivalent source expressed by Eq. (3) is overlapped to the field point.

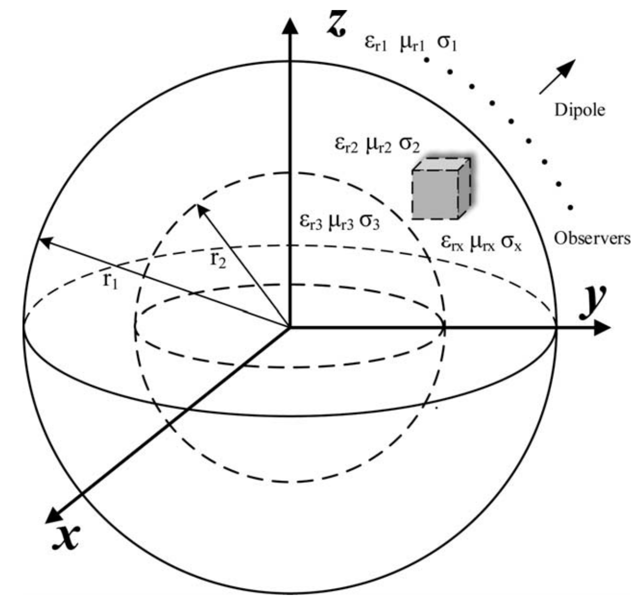

Figure 3 A homogeneous cubic scatterer buried in the middle layer of a three spherically layered medium

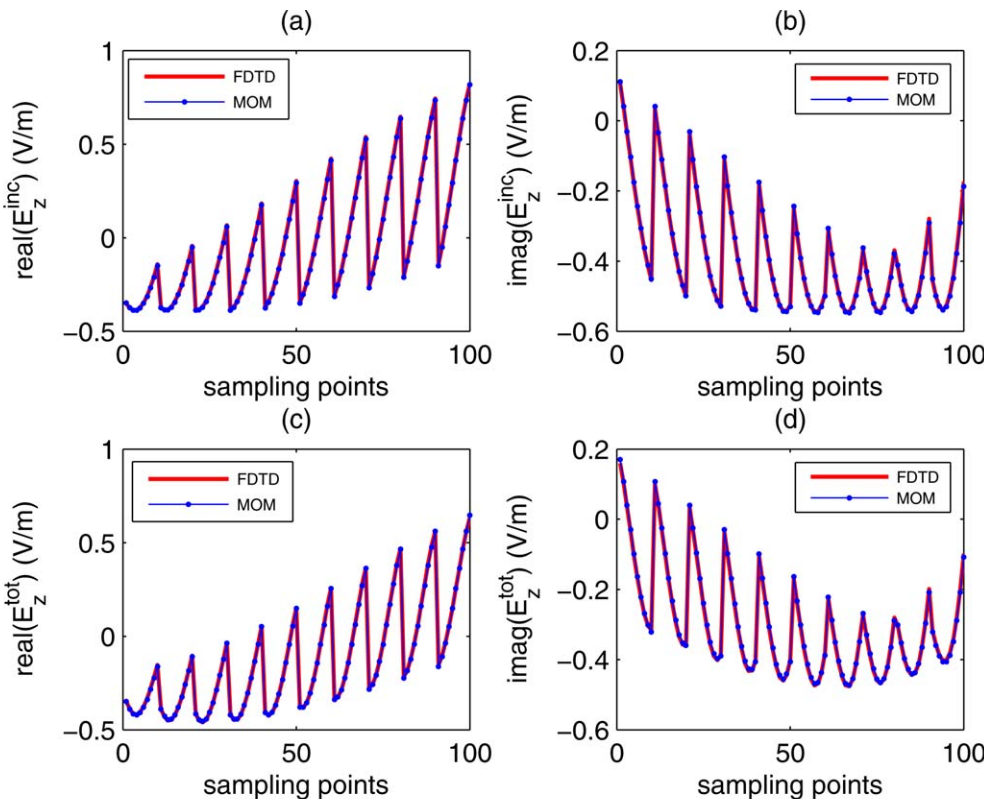

Figure 4 Electric fields inside the cuboid. (a) Real part of incident field E_z^{inc} at z = 4.025 m. (b) Imaginary part of incident field E_z^{inc} at z = 4.025 m. (c) Real part of total field E_z^{tot} at z = 4.025 m. (d) Imaginary part of total field E_z^{tot} at z = 4.025 m. [Color figure can be viewed at wileyonlinelibrary.com]

The aim of this letter is to develop an efficient solution for the EM scattering problems in spherically multilayered media. However, direct discretization of the computational domain in the spherical coordinate is difficult. Thus, we discretize it in the Cartesian system and transform the expressions of the Green's functions solved using Eq. (5) to their expressions in the Cartesian coordinate system. In this way, EM scattering problems in spherically multilayered media can be solved by MOM combined with Krylov subspace iteration method in the EFIE formulated in the Cartesian coordinate system, which, however, has been successfully used to solve EM scattering problems in planarly layered media [3].

A DGF consists of nine scalar elements G_{x_i,x_j} placed in a 3 × 3 tensor matrix, where $i,j\in\{1,2,3\}$ and x_i denotes the basis vector in different coordinate systems in the three dimensional space ($\{x,y,z\}$ in the Cartesian coordinate and $\{r,\theta,\varphi\}$ in the spherical coordinate). Each element decides the effect of an electric dipole source along x_j on the field component along x_i. In the Cartesian coordinate, the basis vectors are the same for both the expressions of current sources at the source point and those of fields at the observation point. However, in the spherical coordinate, the current source at the source point is given in source coordinates (r',θ',φ') while the field at the field point is expressed in the filed coordinates (r,θ,φ). These two local coordinates are the same only if the field point, the source point and the origin location in one straight line, which means $\theta=\theta'$ and $\varphi=\varphi'$.

As illustrated in Figure 2, the basis vectors in the spherical coordinate system at the source and observation points are different. First, the rotation matrix $\bar{\boldsymbol{\eta}}(\theta,\varphi)$ that transforms the vector in the spherical coordinate to that in the Cartesian system is defined as following

$$\begin{bmatrix}\hat{\mathbf{x}}\\ \hat{\mathbf{y}}\\ \hat{\mathbf{z}}\end{bmatrix}=\begin{bmatrix}\sin\theta\cos\phi & \cos\theta\cos\phi & -\sin\phi\\ \sin\theta\sin\phi & \cos\theta\sin\phi & \cos\phi\\ \cos\theta & -\sin\theta & 0\end{bmatrix}\begin{bmatrix}\hat{r}\\ \hat{\theta}\\ \hat{\phi}\end{bmatrix}=\overline{\eta}\begin{bmatrix}\hat{r}\\ \hat{\theta}\\ \hat{\phi}\end{bmatrix} \quad (6)$$

Thus,

$$\begin{bmatrix}G_{xr'} & G_{x\theta'} & G_{x\phi'}\\ G_{yr'} & G_{y\theta'} & G_{y\phi'}\\ G_{zr'} & G_{z\theta'} & G_{z\phi'}\end{bmatrix}=\overline{\eta}\begin{bmatrix}G_{rr'} & G_{r\theta'} & G_{r\phi'}\\ G_{\theta r'} & G_{\theta\theta'} & G_{\theta\phi'}\\ G_{\phi r'} & G_{\phi\theta'} & G_{\phi\phi'}\end{bmatrix} \quad (7)$$

Similarly,

$$\begin{bmatrix}G_{xr'} & G_{x\theta'} & G_{x\phi'}\\ G_{yr'} & G_{y\theta'} & G_{y\phi'}\\ G_{zr'} & G_{z\theta'} & G_{z\phi'}\end{bmatrix}=\begin{bmatrix}G_{xx'} & G_{xy'} & G_{xz'}\\ G_{yx'} & G_{yy'} & G_{yz'}\\ G_{zx'} & G_{zy'} & G_{zz'}\end{bmatrix}\overline{\eta}' \quad (8)$$

Through applying Eqs. (7) and (8), we can easily show that the relationship between the DGF in the Cartesian coordinate and that in the spherical coordinate satisfies the following equation

$$\begin{bmatrix}G_{xx'} & G_{xy'} & G_{xz'}\\ G_{yx'} & G_{yy'} & G_{yz'}\\ G_{zx'} & G_{zy'} & G_{zz'}\end{bmatrix}=\overline{\eta}\begin{bmatrix}G_{rr'} & G_{r\theta'} & G_{r\phi'}\\ G_{\theta r'} & G_{\theta\theta'} & G_{\theta\phi'}\\ G_{\phi r'} & G_{\phi\theta'} & G_{\phi\phi'}\end{bmatrix}\overline{\eta}'^{-1} \quad (9)$$

Note that $\bar{\boldsymbol{\eta}}(\theta,\varphi)$ is an orthogonal matrix. Therefore, $\bar{\boldsymbol{\eta}}^{\boldsymbol{T}}(\theta,\varphi)$ can be used to replace $\bar{\boldsymbol{\eta}}^{-1}(\theta,\varphi)$. The above equation can be simplified to the following format

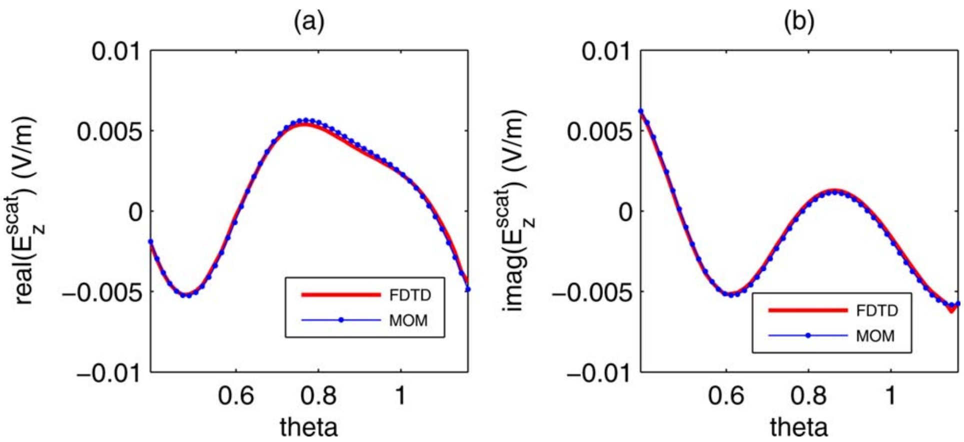

Figure 5 Electric field in receivers located in air. (a) Real part of scattered field E_z^{scat} at the arc of r = 12 m, $\varphi = \pi/4$. (b) Imaginary part of scattered field E_z^{scat} at the arc of r = 12 m, $\varphi = \pi/4$. [Color figure can be viewed at wileyonlinelibrary.com]

$$\overline{\mathbf{G}}_{\text{car}}(\mathbf{r},\mathbf{r}')=\overline{\eta}(\theta,\phi)\overline{\mathbf{G}}_{\text{sph}}(\mathbf{r},\mathbf{r}')\overline{\eta}^T(\theta',\phi') \tag{10}$$

where $\bar{\mathbf{G}}_{\text{car}}$ represents the DGF in the Cartesian coordinate and $\bar{\mathbf{G}}_{\text{sph}}$ stands for the DGF in the spherical coordinate.

2.3. Discretization and Iterative Solver for the Discrete System

In this paper, we use the delta function as the testing function and the pulse function as the basis function to discretize the EFIE into a linear system. We assume the D domain containing the object is divided into $N_x \times N_y \times N_z$ size-independent cells in the Cartesian coordinate. After discretization, the EFIE is transformed into a discrete linear system that can be solved via Krylov subspace iteration method. The BCGS method is employed here to solve the linear Eq. (4). For the volume integral equation, it has been proved by Xu *et al*. [8] that the BCGS method converges much faster than CG [10] and BiCG [11]. The following numerical results also show the accuracy and efficiency of our method.

3. NUMERICAL RESULTS

In order to validate our solver for the EM scattering in spherically multi-layered media, we compare the solutions by using the BCGS iteration method and the results from FDTD simulations by using the commercial software Wavenology EM. Figure 3 shows the geometry of a two spherically layered dielectric sphere located in air with the radius of $r_1=10.0$ m and $r_2=5.0$ m. The layered sphere is located at $(0,0,0)$ m. Considering the existing of air, we treat it as a three spherically layered background. A homogeneous dielectric cuboid with the dimensions $L_x=L_y=L_z=1.5$ m is entirely embedded in the middle layer of the background. The center of the cuboid is located at $(4.25, 4.25, 4.25)$ m. The electric parameters of the cuboid are $\varepsilon_{rx}=4.0$, $\sigma_x=$ 0.002 S/m, $\mu_{rx}=1.0$. The space is characterized by $\varepsilon_{r1}=1.0$, $\mu_{r1}=1.0$, $\sigma_1=$ 0.0 S/m, $r_1=10.0$ m, $\varepsilon_{r2}=2.0$, $\mu_{r2}=1.0$, $\sigma_2=$ 0.001 S/m, $r_2=5.0$ m, $\varepsilon_{r3}=4.0$, $\mu_{r3}=1.0$, and σ_3 = 0.001 S/m. The electric dipole source is in the $\hat{\boldsymbol{r}}$ direction, i.e., $\mathbf{J}=\hat{\boldsymbol{r}}\delta(\mathbf{r}-\mathbf{r}_0)$, where $\mathbf{r}_0=(8.0, 8.0, 8.0)$ m represents the source location in the spherical coordinate system. The operating frequency of the dipole is 50 MHz. The location of observation points in the outmost layer is a function of θ at the arc of r = 12 m, $\varphi = \pi/4$. For convenience, we let the computational domain be the same as the cuboid. And we discretize this domain into $N_x=N_y=N_z=10$ uniform cells, with the dimension of each cell $dx = dy = dz = 0.015$ m. The wavelength inside the cuboid is about 2.986 m. Thus, the sampling rate is about 20 points per wavelength (PPW). For a fair comparison, we use the same sampling rate in FDTD simulations.

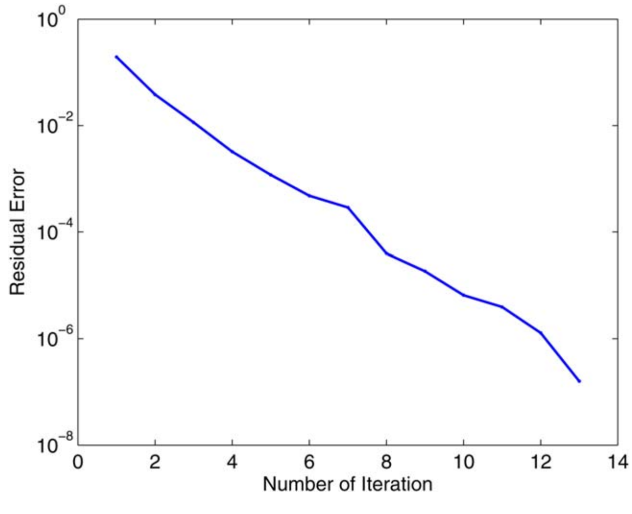

Figure 6 Residual error versus the number of iteration steps. [Color figure can be viewed at wileyonlinelibrary.com]

Figures 4(a) and 4(b) show the comparisons of the z component of incident electric fields in the XY plane at $z = 4.025$ m inside the cuboid near the center between the solutions by using our MOM solver and the results from the FDTD simulations. Figures 4(c) and 4(d) depict comparisons for the total electric fields in the same positions as for the incident fields. Figures 5(a) and 5(b) show the comparisons of the scattered electric fields in the receivers located in air as a function of θ at the arc $r = 12$ m, $\varphi = \pi/4$. Both the total electric fields inside the cuboid and the scattered electric fields in the receivers show good agreements between our MOM solver and the FDTD simulations. Figure 6 shows the residual error versus the number of iteration steps in the BCGS algorithm for the solutions of the total fields inside the cuboid. It is only takes six iterations of our method to make the relative residual error less than 0.05%. The BCGS method is accurate and efficient for the EM scattering problems in spherically multilayered media.

4. SUMMARY

The main contribution of this letter is the development of a MOM solver combined with the Krylov subspace iteration method for the EM scattering problem of inhomogeneous objects buried in spherically multilayered media. The DGF in spherically multilayered media is constructed in terms of the spherical vector by using the method of scattering superposition in the spherical coordinate. These expressions were later transformed to the expressions in the Cartesian coordinate system. The computational domain is discretized in the Cartesian coordinate system and the EFIE in this system was solved by using the BCGS iteration method. Numerical results validate the accuracy and efficiency of our method to solve the scattering problems in spherically multilayered media.

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CO-DESIGN OF TWO-WAY DOHERTY POWER AMPLIFIER AND FILTER FOR CONCURRENT DUAL-BAND APPLICATION

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ABSTRACT: *In this letter, an architecture is presented to solve problems of classical concurrent dual-band Doherty power amplifiers (DPAs) and its design procedure is given. It is a codesign of two single-band DPAs and four filters. Two of filters at the output port are used for impedance transformation, harmonic components suppressing and signal isolating, while the another two split concurrent dual-band signals at the input port. In this way, intermodulation components of the two bands can be effectively suppressed and each band can achieve a good performance as single-band one's. This design concept is demonstrated through implementing of a practical dual-band DPA operating at 1.8 and 2.5 GHz. Measurement results show that efficiencies are 65.0 and 56.3% at the 6 dB output power back-off for concurrent application. The intermodulation components and harmonic components are lower than −40 dB except second harmonic component at 1.8 GHz (−32 dB).*

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Key words: *dual-band; two-way; doherty; filter; concurrent*

1. INTRODUCTION

POWER amplifier (PA) is an energy consuming component in the wireless communication systems. While the conversion efficiency is still not satisfied in that it is meaningful for broadband or multi-band PAs research [1–5]. Considering wide-band signals with high peak to average power ratio (PAPR), Doherty power amplifier (DPA) is naturally became a good choice because it has another peak efficiency at the output power back-off (OBO) region resulting in higher efficiency for high PAPR signals. Dualband DPAs are more competitive than wide-band ones for concurrent dual-band application, since it has larger possibility to achieve a better performance. However, the performance of traditional dua-band DPA is still incomparable with narrow band DPA, such presented in [6–8]. Under the concurrent mode, traditional dual-band PAs [9,10] have lower gain than single mode and will generate harmful intermodulation components. This is non-negligible issue [11]. In view of the these factors, an architecture who contains two DPAs and four filters is proposed to solve these problems. The filters with simple structure possess characteristics of harmonic suppressor, impedance transformer and duplexer, and become a part of DPA's matching network. To prove this architecture, theory analysis and a design example are given in this article.

2. ANALYSIS OF THE PROPOSED ARCHITECTURE

The proposed architecture is displayed in Figure 1. This DPA contains two ways, each of which has two parts (two filters and a DPA named as *Sub-DPA)* and it only operates on a band.

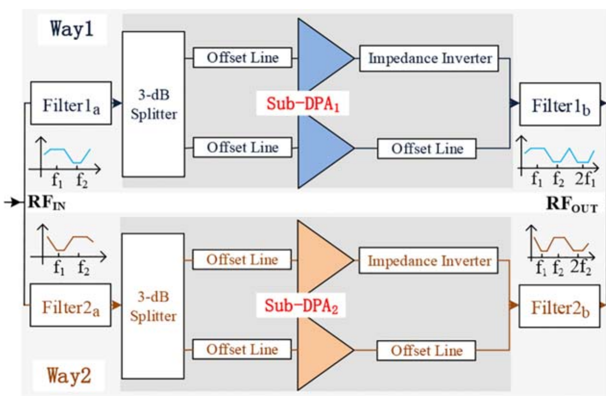

Figure 1 The simplified block diagram for the proposed two-way concurrent dual-band Doherty. [Color figure can be viewed at wileyonlinelibrary.com]