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ELECTROMAGNETIC CHARACTERISTICS OF CONFORMAL DIPOLE ANTENNAS OVER A PEC SPHERE

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Abstract—Rigorous mathematical Method of Moments (MoMs) for analyzing various radiating spherical structures is presented in this paper by using Dyadic Green's Functions (DGFs) in conjunction with Mixed Potential Integral Equation (MPIE) formulation. With the aid of linear Rao-Wilton-Glisson (RWG) triangular basis functions and by converting spherical DGFs to Cartesian DGFs, a conformal dipole antenna in free space and over a Perfect Electric Conductor (PEC) sphere is analyzed. The characteristics of such antennas are computed by applying multilayer spherical DGFs and asymptotic approximation methods. Mutual couplings between elements of a conformal dipole antenna array in free space and over a conducting sphere are also investigated. Good agreement between the computational results obtained by the proposed methods and those obtained from commercial simulator packages shows accuracy and high convergence speed of the presented methods.

1. INTRODUCTION

By using Dyadic Green's Functions (DGFs), a field component can be expressed in terms of a current vector component [1, 2]. Deriving appropriate DGFs for analyzing electromagnetic boundary or eigenvalue problems results in substantial simplification and compactness [1]. Although most of the problems can be solved without DGFs, it is more efficient to use dyadic Green's functions. It should be noted that DGFs have been calculated only for some canonical structures and for many cases vector wave functions should be used to

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obtain DGFs suitable for those particular problems. Electromagnetic fields in a specific direction have been calculated for a small electric and magnetic dipole located inside a multilayer sphere [3]. In [4], an antenna structure over cylindrical shell has been analyzed by using spectral domain Green's functions. The resonance problem of a circular microstrip disk mounted on a spherical surface has been studied theoretically by utilizing Green's function formulation in spectral domain [5]. The resonant frequencies for the lossless spherical cavity filled with a Chiral medium are obtained from the dyadic Green's functions [6]. Closed form equations using DGFs containing a series of spherical harmonics have been used to evaluate electric and magnetic fields in such structures [2]. In [7], DGFs have been expanded asymptotically resulting in a significant increase in convergence rate of spherical harmonics series. With this approach, conformal antenna problems have been solved by evaluating DGFs coefficients in [8] using spherical Bessel and Hankel functions approximation for large arguments. Asymptotic approximation method presented in [7] yields a higher convergence speed in the calculation of antenna input impedance but it cannot be utilized for radiation pattern determination since field and source points are not at the same distance from the sphere center in this case. In [9], a Hybrid Finite Element-Boundary Integral (FE-BI) formulation is introduced, employing asymptotic spheroid DGFs for design of doubly curved conformal antennas. A combination of the Finite Difference Time Domain (FDTD) and MoMs is applied to solve the problem of radiation from conformal aperture and microstrip antennas mounted on arbitrarily-shaped conducting bodies [10]. Most of the MoMs approaches mentioned above consider specific current distribution on antenna elements. It is known that modal analysis which is a part of procedure for field calculation by MoMs suffers from some shortcoming when number of modes increases. This is due to prior specific current distribution considered. Complexity of meshing the structures is another drawback encountered in problems where the antenna elements are segmented into curvilinear cells.

In this paper, explicit formulas are derived to analyze various radiating structures where source regions are divided into linear triangles. Then a spherically conformal dipole antenna fed at its center located in free space is analyzed. Thereafter using DGFs, the input admittance and radiation pattern of such a dipole antenna over a PEC sphere are presented. In this paper, DGFs transformation from spherical to Cartesian coordinates is also accomplished, which is used to efficiently compute radiation fields of various spherical antenna structures with linear triangular mesh generations. In order to validate the presented method, the antenna is also analyzed by meshing the PEC sphere and conformal dipoles into linear triangles and using free space Green's functions. Mutual couplings between the elements of a conformal dipole antenna array located in free space or over a conducting sphere are investigated. Comparison of the results obtained from the proposed method with those of CAD simulations clearly shows the ability and accuracy of presented method.

2. THE PROPOSED FORMULATION

One of the efficient numerical methods with high preprocessing gain for solving electromagnetic structures is the method of moments where the source region must be divided into cells. In this method, the unknown functions which are usually the source currents or charges are obtained via an integral equation formulation with appropriate Green's functions. Such integral equations can be in space domain, spectral domain, or both of these two domains. In general due to meshed finite source region, methods based on integral equation formulations are more accurate and require less memory and time [11]. For any class of integral equations namely Electric Field Integral Equation (EFIE), Magnetic Field Integral Equation (MFIE) or Mixed Potential Integral Equation (MPIE), appropriate type of Green's functions should be used. EFIE has the advantage of being applicable to both open and closed structures, whereas MFIE applies only to closed surfaces [12]. A set of formulation which uses auxiliary potentials and leads to MPIE formulation is weakly singular and can be easily utilized in MoMs formulation. Many researches have been reported to calculate input impedance and radiation pattern of an antenna using MPIE formulation [13]. Dividing the source region into small triangles and considering the common edge between two adjacent cells as a current element, and expanding the current into triangular basis functions ($\mathbf{f}_n$) [12], the source current can be defined as:

$$\mathbf{J}_s = \sum_{n=1}^{N} I_n \mathbf{f}_n \tag{1}$$

Here N is the number of non-boundary edges and I_n coefficients are to be obtained from MPIE formulation [13]. Therefore if the source region is segmented by linear triangular cells, unknown current coefficients in the antenna can be determined by applying RWG basis functions and satisfying the boundary conditions. In this case the electric field considered as:

$$\mathbf{E} = -j\omega\mathbf{A} - \nabla\psi, \tag{2}$$

where $\mathbf{A}$ is magnetic vector potential and ψ the electric scalar potential as defined in [14]. Since tangential component of electric field vanishes on perfect conducting metal, impedance matrix by applying MPIE and Galerkin's method can be written as:

$$Z_{pq}=-\iint_{s}\iint_{s'}\left[j\omega f_p(\mathbf{r})\cdot\bar{\mathbf{G}}_A\cdot f_q(\mathbf{r}')+(\nabla\cdot f_p(\mathbf{r}))\,G_\psi(\nabla'\cdot f_q(\mathbf{r}'))\right]ds'ds, \quad (3)$$

in which $\bar{\mathbf{G}}_A$ and G_ψ are respectively the magnetic dyadic and the electric scalar Green's functions. These functions are presented in spherical coordinates in [14].

$\mathbf{r}(r,\theta,\varphi)$ and $\mathbf{r}'(r',\theta',\varphi')$ refer to field and source position vectors, respectively. $f_{p,q}(\mathbf{r})$ are triangular basis functions defined in [12]. The integration over the testing triangles can be avoided by using the centers of field triangular cells and approximate Galerkin's method [12]. Therefore, the integration is performed only over source triangles by applying 3-point Gauss quadrature method. In this case, by applying the aforementioned integration method, no singularity will be encountered in the integration. Therefore, there is no need to solve the double integration analytically in the singular points of the integrands as done in [11]. For a structure with homogenous media, it is expected that the impedance matrix calculated from MoMs will be symmetric and diagonally dominant.

Figure 1(a) illustrates a conformal dipole antenna located in free space or in the vicinity of a PEC sphere. As shown in Fig. 1(b), the structure can be divided into three regions. The conformal antenna is located at the boundary of layers 1 and 2. Region 3 may be considered as free space or PEC. In the latter case, the conducting medium is modeled by $\varepsilon\to\infty$, $\mu\to 0$ in order for the propagation constant to be finite and numerical modeling of the antenna to be feasible [7].

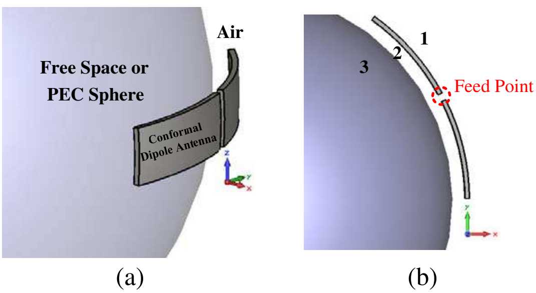

Figure 1. (a) A conformal dipole antenna in free space or over PEC sphere, (b) 3-layer sphere and the antenna feed point model.

It should be noted that input impedance formula of a conformal antenna over a spherical shell can be extracted using addition theorem for spherical Hankel functions yielding asymptotic formulation with more convergence speed [15]. For conformal antenna over a multilayer sphere, when both source and field points are at the same distance from the sphere center, we do not need to consider $\bar{\mathbf{G}}_A^{(fs)}$ and it is only enough to compute $G_\psi^{(f\,s)}$ [7]. Therefore, input impedance of antennas located on a multilayer sphere can be obtained by using DGFs or asymptotic approximation formulas in MPIE.

2.1. Conformal Dipole Antenna in Free Space

When antenna is located in an unbounded free space, scalar wave equations can be applied instead of dyadic forms for calculation of impedance matrix resulting in the following equation:

$$Z_{pq}=\iint\limits_{s'}\left[\frac{j\omega\mu}{4\pi}f_p(\mathbf{r}^{c\pm})\cdot f_q(\mathbf{r}')g+\frac{1}{j4\pi\omega\varepsilon}\big(\nabla\cdot f_p(\mathbf{r}^{c\pm})\big)\big(\nabla'\cdot f_q(\mathbf{r}')\big)g\right]ds', \quad (4)$$

where $g = e^{-jkR}/R$ and $c+$ or $c-$ denotes the center of positive or negative triangles, respectively. Therefore, scalar unknown coefficients of current distributions are determined on the common edges between two adjacent triangles by computing impedance and antenna excitation matrices. Electric field vector can be calculated from Equation (2) or by integrating posterior scalar product of DGFs and current vectors over the source region as described in the following equation:

$$\mathbf{E} = -j\omega\mu_f \iint\limits_{s'} \bar{\mathbf{G}}_E^{(fs)} \cdot \mathbf{J}(r')ds', \quad (5)$$

in which $\bar{\mathbf{G}}_E^{(fs)} = \bar{\mathbf{G}}_{0E}^{(fs)}$ is DGFs in an unbounded free space and is defined by:

$$\bar{\mathbf{G}}_{0E}^{(fs)} = \left(\bar{\mathbf{I}} + \frac{1}{k_f^2}\overline{\nabla\nabla'}\right) G_0, \quad (6)$$

$$G_0 = \frac{e^{-jk_f\,R}}{4\,\pi\,R}, \quad (7)$$

where k_f is the propagation constant in free space. In order to simplify computation procedure, Cartesian DGFs of free space may be used when source and field points are both located in free space. It can be written with the aid of Equation (6) as follows:

$$R = \sqrt{(x-x')^2+(y-y')^2+(z-z')^2} \tag{8a}$$

$$\bar{\mathbf{G}}_{0E}^{(fs)} = \begin{pmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{pmatrix} \tag{8b}$$

$$G_{uu} = \frac{\left[\begin{array}{l} e^{-jk_fR}\Big(-R^2-jk_fR^3+k_f^2R^4+3\,(u-u')^2 \\ -k_fR\,(-3j+k_fR)\,(u-u')^2\Big) \end{array}\right]}{4k_f^2\pi R^5}, \tag{8c}$$

$$G_{uv} = -\frac{e^{-jk_fR}\Big(-3-3jk_fR+k_f^2R^3\Big)(u-u')(v-v')}{4k_f^2\pi\, R^5};\ u \neq v, \tag{8d}$$

where $u, v = x, y, z$ and $G_{u\,v} = G_{v\,u}$ because of symmetrical properties of DGFs.

2.2. Conformal Dipole Antenna in the Vicinity of a Conducting Sphere

For full wave analysis of a conformal dipole antenna over a PEC sphere, the scattering components of DGFs ($\bar{\mathbf{G}}_{es}^{(fs)}$) must be taken into consideration. By considering source and field points in layer 1 $\bar{\mathbf{G}}_{E}^{(11)} = \bar{\mathbf{G}}_{0E}^{(11)} + \bar{\mathbf{G}}_{es}^{(11)}$ in which $\bar{\mathbf{G}}_{es}^{(11)}$ is as follows:

$$\begin{aligned} \bar{\mathbf{G}}_{es}^{(11)} &= \frac{jk_1}{4\pi}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(2-\delta_m^0\right)\frac{2n+1}{n\,(n+1)}\frac{(n-m)!}{(n+m)!} \\ &\quad\times\left\{\begin{array}{l} b_M^{11}\mathbf{M}^{(2)}_{\substack{e\\o}mn}(k_1)\mathbf{M}'^{(2)}_{\substack{e\\o}mn}(k_1) \\ +\,b_N^{11}\mathbf{N}^{(2)}_{\substack{e\\o}mn}(k_1)\mathbf{N}'^{(2)}_{\substack{e\\o}mn}(k_1) \end{array}\right\}, \end{aligned} \tag{9a}$$

where δ_m^0 is the Kronecker delta, and $\mathbf{M}, \mathbf{N}$ vectors are r-dependent eigenvectors in spherical coordinate system with orthogonal properties explained in [2]. Superscript (2) denotes spherical Hankel function of the second kind. $b_{M,N}^{11}$ are the dyadic coefficients expressed as [8]:

$$b_{M,N}^{11} = -\frac{R_{F2}^{H,V}T_{F1}^{H,V}+R_{F1}^{H,V}T_{P1}^{H,V}}{R_{F2}^{H,V}R_{P1}^{H,V}T_{F1}^{H,V}+T_{P1}^{H,V}} \tag{9b}$$

Convergence speed of multilayer spherical DGFs is related to the radii of spheres and permittivities of layers. More spherical harmonic terms should be considered for greater radii and permittivities. Calculation of the double-summation of above DGFs is exhausting and time-consuming since there are spherical harmonics in wave equation solution in spherical coordinates. The double summation in the spherical DGFs can be reduced to an expression with only a single summation by using the following relation [13]:

$$P_n(\cos\gamma)=\sum_{m=0}^{n}\left(2-\delta_m^0\right)\frac{(n-m)!}{(n+m)!}\times P_n^m(\cos\theta)P_n^m(\cos\theta')\cos\left(m(\varphi-\varphi')\right), \quad (10)$$

where $\cos\gamma = \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\varphi-\varphi')$.

Therefore, the convergence speed of DGFs computation increases by converting the double summation of spherical harmonics to a single summation. To achieve to a precise calculation of far fields with an error of about 1%, using the 20 first terms in the summation is sufficient. In the presented method, it takes about 7 minutes to compute radiation pattern (with 60 divisions of φ) with a Core 2 Quad @ 2.86 GHz processor. The fast computation time of this method is considerable in comparison with CAD simulator packages.

Free space Green's functions can also be used to analyze this antenna. In this case, the PEC sphere should also be meshed by linear triangles and current distributions on common edges are computed by solving MPIE. Electric field components can be calculated by utilizing Equation (2) or Equation (5). Fig. 2 illustrates a conformal dipole antenna over a meshed conducting sphere with 840 triangles and 1260 common edges. Due to large number of triangular cells, this method takes more memory and time in comparison with asymptotic approximation or multilayer spherical DGFs methods.

2.3. Array of Conformal Dipole Antennas

The presented method can be utilized to investigate mutual couplings between antenna elements of a conformal dipole antenna located in

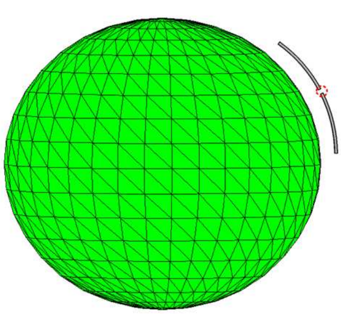

Figure 2. A conformal dipole antenna over a meshed PEC sphere.

free space or above a PEC sphere. Scattering matrix can be calculated as follows [16]:

$$[S] = (Y_0\,[I] + [Y])^{-1}\,(Y_0\,[I] - [Y])\,, \tag{11}$$

where I is the identity matrix and Y admittance matrix. Y_0 is considered as characteristic admittance of feed network. As delta gap voltage is used to excite the electric dipoles, it is advantageous to compute scattering matrix from admittance matrix. The components of admittance matrix are defined as:

$$Y_{ij} = \left.\frac{I_i}{V_j}\right|_{V_i=0,\, i\neq j} \tag{12}$$

Therefore, for an array consisting of N elements, coupled currents due to an excited element on the center of the unexcited elements should be calculated.

2.4. Spherical to Cartesian Transformation of DGF

In order to obtain electromagnetic field components, we require multiplying DGFs and current element vector components for the case of interest. In order to perform multiplication, both DGFs and current vectors should be in the same coordinates. For the case that conformal antenna area is divided into curvilinear triangles as shown in Fig. 3(a), current components to be considered are J_φ and J_θ which are in harmony with spherical components of DGFs [8]. However curvilinear meshing is complicated as compared with linear triangular meshing considered in this paper.

As current elements on common edges of linear meshes have Cartesian components, a new approach for dyad and vector multiplication is presented in this subsection. In order to multiply current vectors and DGFs, either Cartesian current vectors should be

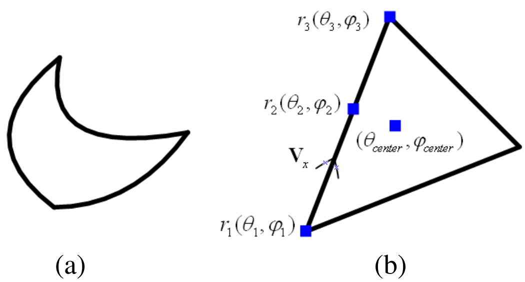

Figure 3. (a) Curvilinear triangle, (b) Linear triangle.

converted to spherical vectors or spherical DGFs should be converted to Cartesian ones. Converting a current vector $\mathbf{V}$; which connects two vertices of a triangle; from Cartesian to spherical coordinates results in a non-unique vector because J_φ and J_θ are different in each point on the edge such as $\mathbf{V}_x$ shown in Fig. 3(b). Since there are unique transformations of vectors from spherical to Cartesian coordinates, conversion of a spherical dyad to a Cartesian dyad can be exactly implemented. Therefore, by employing the centers of the field and source triangles in the calculation of DGFs in Cartesian coordinates the electric field vector can be expressed as:

$$\mathbf{E}^{(Cartesian)} = -j\omega\mu_f \iint_{s'} \bar{\mathbf{G}}^{(Cartesian)} \cdot \mathbf{J}^{(Cartesian)}(\mathbf{r}')ds' \qquad (13)$$

Thus by using triangular linear meshes in Cartesian coordinates only $\bar{\mathbf{G}}$ needs to be converted from spherical to Cartesian coordinates. For this purpose, each unit vector should be transformed from spherical to Cartesian coordinates. As DGFs represent interactions between field and source points, the first and second vectors of each dyad correspond to field and source points respectively. All spherical dyad components can be converted to Cartesian dyads. As an example the conversion equation of $\hat{r}\hat{\varphi}$ component of a dyad is extracted as follows:

$$\hat{r}\hat{\varphi} = (\sin\theta_f \cos\varphi_f \hat{x} + \sin\theta_f \sin\varphi_f \hat{y} + \cos\theta_f \hat{z})(-\sin\varphi_s \hat{x} + \cos\varphi_s \hat{y}), \quad (14)$$

where subscripts f and s refer to field and source points, respectively. Therefore, the Cartesian DGFs compatible with vector currents components can be obtained by using the aforementioned conversion method. Using this approach is efficient when a vector is requested as the output of an antenna problem solution. For example to determine the near and far field radiation patterns of an antenna all E_x, E_y, E_z components of electric field can be calculated.

3. RESULTS

To validate the present computation, a spherical dipole antenna is analyzed which is considered first in free space and then 0.32 cm above a 5 cm radius conducting sphere. Then, conformal dipole antenna arrays in both cases are analyzed. In all cases, antenna physical lengths is $\lambda/2$ with λ being the wavelength at $f = 3\,\mathrm{GHz}$. The medium between the antenna and the sphere is assumed to be free space. It is expected that the antenna response is similar to a linear thin $\lambda/2$ dipole antenna which is presented in [13]. In these examples the antennas have negligible thicknesses in comparison with wavelength and are located in xy-plane as shown in Fig. 1(b). The antenna in each case is divided to 120 triangular linear meshes yielding 119 common edges between two adjacent plus and minus triangles. The delta gap voltage source is used to excite the dipoles. Impedance matrix and current distribution on common edges are computed using MoMs. Besides utilizing DGFs, asymptotic approximation method is also used.

3.1. Spherical Dipole Antenna in Free Space

As the first example a spherical dipole antenna which is fed from its center and located in free space is presented. Antenna input admittance is determined using MoMs and solving MPIE by both asymptotic approximation formulas [7] and DGFs proposed in [14] with unit dielectric constants in all three layers. The results are compared with those obtained from CST Microwave Studio simulator [17]. As illustrated in Fig. 4, good agreement is obtained between all results and little differences are due to probe modeling in CST simulation.

The antenna center is in xy-plane and about 30° from the origin according to the antenna structure. The radiation pattern as expected direct to 30° and 210°. Auxiliary potential equations as well as electric field equations can be utilized to compute radiation pattern. Fig. 5 demonstrates radiation patterns obtained from MoMs using DGFs and CST simulator which are in good agreement.

3.2. Spherical Dipole Antenna over a PEC Sphere

In this section a spherically conformal dipole antenna fed from its center and located above a PEC sphere is analyzed. To show input admittance convergence speed toward spherical harmonics, the input

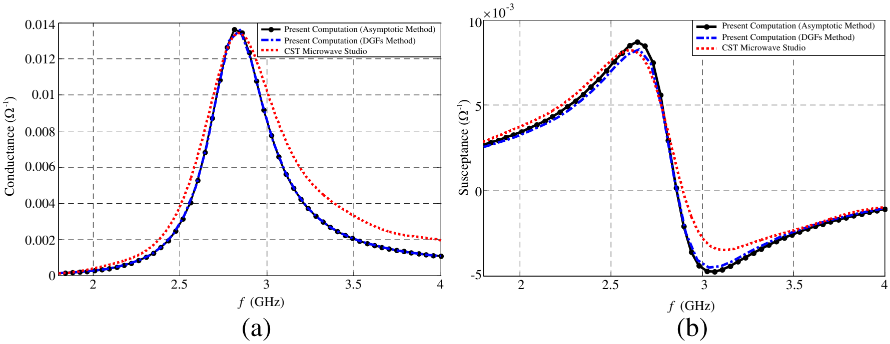

Figure 4. Input Admittance of a spherical dipole antenna in an unbounded free space medium. (a) Conductance, (b) susceptance.

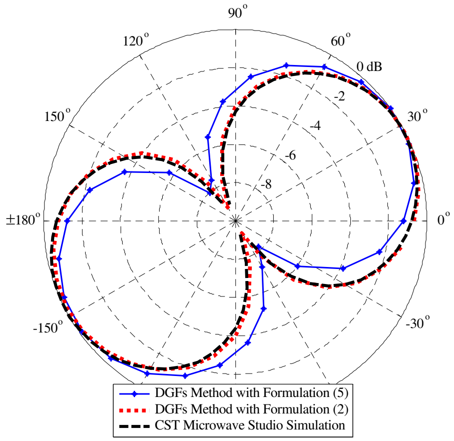

Figure 5. Radiation pattern of a spherical dipole antenna in an unbounded free space medium.

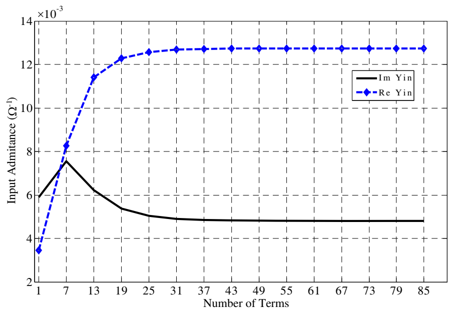

Figure 6. Convergence of input admittance of a spherical dipole antenna over sphere.

admittance at the center frequency of the antenna versus the number of terms in spherical harmonics series is illustrated in Fig. 6.

To analyze a dipole antenna located arbitrarily in a 3-layer dielectric sphere with the same dimensions of the presented example, at least 60 terms of spherical harmonics series are required in order to DGFs be convergent. However, for the case that current elements are located coformally and layers 1 and 2 are considered as free space and layer 3 as PEC, a convergence in antenna input admittance is achieved by considering 25 terms in the series. For input admittance calculation, due to conformal current distribution on the dipole, magnetic potential DGFs are zero [7]. Fig. 7 illustrates the results.

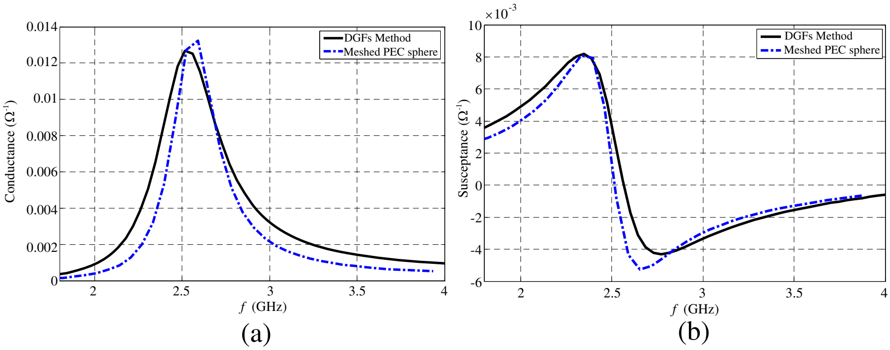

Figure 7. Input admittance of a spherical dipole antenna over PEC sphere. (a) Conductance, (b) susceptance.

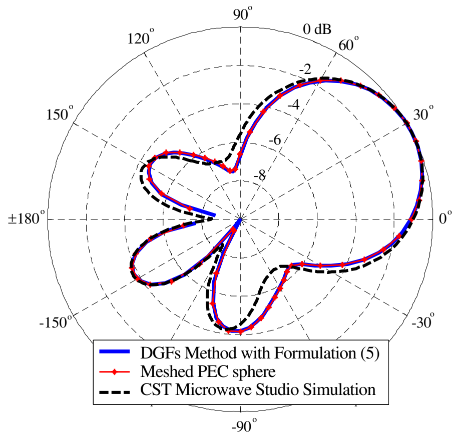

Figure 8. Radiation pattern of a spherical dipole antenna over PEC sphere.

Electric field DGFs with 20 terms of spherical harmonics is used to determine antenna radiation pattern. Fig. 8 compares computed radiation pattern of the antenna with the results obtained from CST software. As it can be seen from this figure, radiation pattern is directed to about 30°. It should be mentioned that at the shadow boundary on the conducting sphere the incident wave excites creeping waves propagating along the sphere surface. Due to comparable dimension of the sphere to the wavelength, the creeping waves radiate surface diffracted waves [18].

3.3. Array of Conformal Dipole Antennas

In the following, two examples of conformal dipole antenna arrays located at the same radial distance from the center of coordinates (Fig. 9) are analyzed and mutual couplings between their elements are investigated d defined in degrees represents the distance between the centers of elements and can be in θ or φ direction.

Figure 10 shows insertion loss and mutual coupling of a pair of spherical dipole antennas separated by a distance of 15° in θ direction from each other and located in free space or above a conducting sphere.

Some changes in the results can be noticed from Fig. 10 with and without the presence of the conducting sphere. Fig. 11 demonstrates mutual coupling between two conformal dipoles over a PEC sphere for different separation distances in θ direction.

Mutual coupling between a pair of spherical dipoles located in free space or above a conducting sphere is studied at the center frequency of the antennas and is illustrated versus d in φ direction in Fig. 12.

Mutual couplings between the elements of an array of five conformal dipoles above a PEC sphere are also investigated. Each

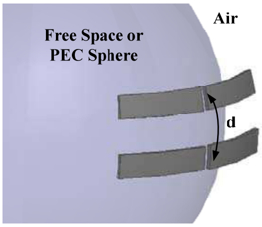

Figure 9. A pair of conformal dipole antennas.

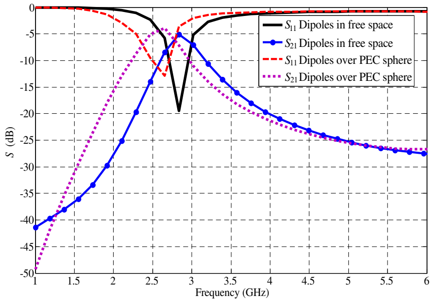

Figure 10. S-parameters of a pair of conformal dipole antennas.

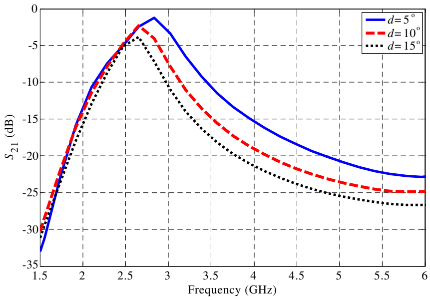

Figure 11. Mutual coupling of a pair of conformal dipole antennas over a PEC sphere.

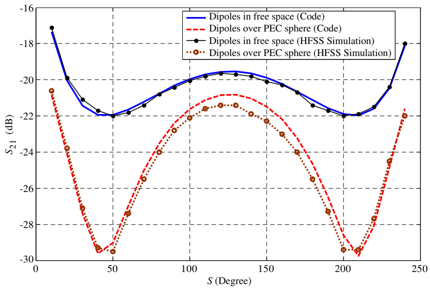

Figure 12. Mutual coupling of a pair of conformal dipole antennas versus d in φ direction.

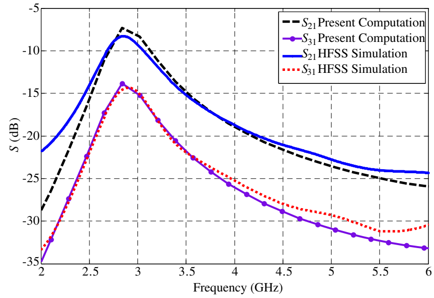

Figure 13. Mutual couplings of an array of five conformal dipole antennas over a PEC sphere.

antenna element is separated from its adjacent element by a distance of 15° in θ direction and the lowest dipole is considered as the first element. Fig. 13 shows the mutual couplings between the first three adjacent elements obtained from the presented method and Ansoft HFSS simulation. As it can be noticed, good agreement between the results is achieved.

It can be noticed that the results obtained from the presented analysis methods based on DGFs or asymptotic approximation are in good agreement with the results obtained from HFSS and CST softwares. However, simulator packages are highly dependent on meshing the structure, probe modeling and the size of radiation box. Therefore, more time and memory is required in order to obtain precise and stable results from simulator packages. The proposed methods have more calculation speed and accuracy in comparison with the mentioned softwares.

4. CONCLUSION

In this paper, full-wave methods to analyze various antennas in free space or over spherical multilayer structures have been presented. In these methods, after meshing the antenna into linear triangles in Cartesian coordinates, the input admittance of a conformal dipole antenna over a PEC sphere has been computed by using MPIE formulation. The infinite double summation has been transformed to a single summation using addition theorems for Legendre polynomials and spherical Hankel functions yielding an increase in the radiation pattern computation convergence speed. In order to determine electric field vectors at entire medium, converting dyads from spherical to

Cartesian coordinates has been presented. To validate the proposed methods, mutual couplings between elements of a conformal dipole antenna array in free space or above a conducting sphere have been investigated. Accuracy of the proposed methods has been validated by comparing the results obtained by the presented methods with those obtained from commercial softwares.

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