Theory and Experiment of Parasitic Element Effects on Spherical Probe-Fed Antenna

Javad Soleiman Meiguni*
Faculty of Electrical and Computer Engineering, Assistant Professor Semnan University, Semnan, Iran
javad.meiguni@ieee.org
Manouchehr Kamyab
Faculty of Electrical and Computer Engineering, Professor K. N. Toosi University of Technology, Tehran, Iran
kamyab@eetd.kntu.ac.ir
Ahmad Hosseinbeig
Faculty of Electrical and Computer Engineering, K. N. Toosi University of Technology, Tehran, Iran
hosseinbeig@ieee.org

Received: 22/Aug/2013 Accepted: 22/Oct/2013

Abstract
Theory and experiment of a spherical probe-fed conformal antenna with a parasitic element mounted on a spherical multilayer structure are presented in this paper. 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. Linear Rao-Wilton-Glisson (RWG) triangular basis functions are applied in MPIE formulation. Current distributions on coaxial probe and conformal radiating elements are computed by using spatial domain Dyadic Green's Function (DGF) and its asymptotic approximation. A prototype of such an antenna is fabricated and tested. The effect of the parasitic element on the input impedance and radiation patterns of the antenna is investigated. It is shown that the antenna characteristics are improved significantly with the presence of the conducting parasitic element. Good agreement is achieved between the results obtained from the proposed methods and the measurement results.

Keywords: Asymptotic Approximation; Dyadic Green’s Function; Spherical Probe-Fed Antennas.

1. Introduction

Probe-fed microstrip antennas embedded in layered spherical media have been studied theoretically and experimentally in recent years. Linear or circular polarizations can be achieved by proper design of these antennas making them applicable in base station satellite communication systems. There is an increasing interest of using microstrip antennas in aerodynamic applications due to their low profile, ease of fabrication and conformability.

Full-wave analysis of these antennas can be advantageous in design procedure. Full-wave numerical techniques based on Green's functions of the structures are too efficient and fast [1]-[3]. In [4]-[5], full-wave analysis of an arbitrary shape aperture coupled antenna placed on a layered sphere has been investigated by using spherical DGFs in combination with electromagnetic fields integral equation formulations. Radiation properties of a hemispherical dielectric resonator antenna, consisting of a monopole antenna placed in a dielectric hemisphere have been theoretically examined in [6]. The effect of a dielectric superstrate on the radiation pattern of a rectangular microstrip patch antenna has been investigated based on the spectral-domain MoMs in conjunction with the stationary phase method [6]-[7]. In [8], a numerical method has been presented to analyze stacked microstrip antennas considering the shape of the radiating elements, the junction of the probe, and the feed current. A strip model in the volume-surface integral equation (VSIE) formulation has been used to simplify the analysis of the probe-fed conformal microstrip antennas with arbitrary shapes [9]. An approach based on hybrid volume-surface integral equation formulation in combination with spherical dyadic Green's function (DGF) is presented in [10] to analyze aperture-coupled multilayer hemispherical dielectric resonator antennas (DRA) with conformal conducting patches.

In this paper, in order to model probe and patches with arbitrary shapes, RWG method [11] is used to analyze spherical probe-fed antennas with parasitic elements. Spherical DGF is applied in the moment’s method formulation. As conformal radiating elements are considered in this paper, asymptotic approximation approach is

* Corresponding Author

also expressed. To validate the proposed method, a prototype of this antenna is implemented and tested. Comparison of the measured and calculated input impedance and radiation patterns shows good agreement between the results.

2. Theory

Figure 1 shows a conformal microstrip antenna and a conducting parasitic stack embedded in a four-layer sphere. A PEC sphere is located in the core of the structure and can be assumed as the antenna ground plane. The parasitic patch improves impedance characteristic and directivity of the antenna. In order to compute current distributions on the patches, MoM in conjunction with DGF of a four-layer sphere is used [12].

2.1 Mixed Potential Integral Equation Formulation

One of the efficient numerical methods with high pre-processing gain for analyzing electromagnetic structures is the method of moment where the source region must be divided into small cells. In this method, the unknown source currents are obtained via an integral equation formulation with appropriate Green's function. Such integral equations can be in space domain, spectral domain, or both of these two domains. In general, due to meshing the finite area source, methods based on integral equation formulations are more accurate and require less memory and time. 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 function should be used [11-12]. A set of formulation which uses auxiliary potentials and leads to MPIE formulation is weakly singular and can be easily applied in MoM.

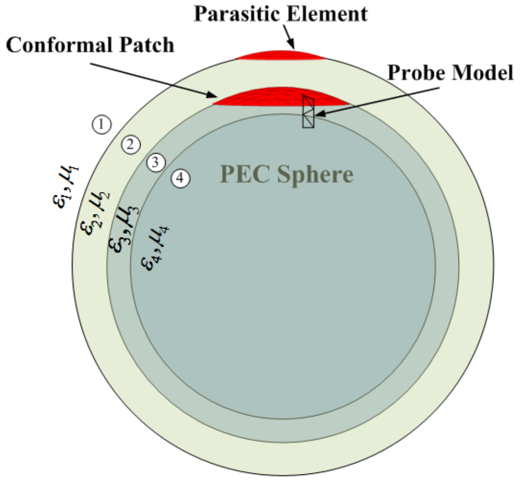


Fig. 1 Conformal patch and parasitic element with probe-fed modeling on a layered sphere.

To apply MoM, conducting surfaces are meshed with linear triangles and Rao-Wilton-Glisson (RWG) triangular basis functions are used to compute current distributions on common edges between two adjacent cells [11]. Hence, the surface current and electric flux densities are expanded in terms of their corresponding basis functions as follow:

$$\mathbf{J}_s(\mathbf{r}) = \sum_{n=1}^{N_M} I_n \mathbf{f}_n^S(\mathbf{r}), \tag{1}$$

In order to derive MPIE formulation in dyadic space, magnetic potential DGF ($\bar{G}_A$) and electric scalar Green's function (G_ψ) are required. $\bar{G}_A$ can be formulated by equating EFIE (2a) with MPIE (2b) and using integral and vector equivalence theorems:

$$\mathbf{E} = -j\,\omega\,\mu_f \iint_{s'} \overline{\mathbf{G}}_E^{(fs)} .\mathbf{J}(\mathbf{r}')ds', \tag{2a}$$

$$\mathbf{E} = -j\,\omega\,\mathbf{A} - \nabla\psi = -j\omega\mu_f \iint_{s'} \overline{\mathbf{G}}_A^{(fs)} .\mathbf{J}(\mathbf{r}')ds' - \nabla \iint_{s'} \nabla' G_\psi^{(fs)} .\mathbf{J}(\mathbf{r}')ds', \tag{2b}$$

$$\overline{\mathbf{G}}_A^{(fs)} = \overline{\mathbf{G}}_E^{(fs)} - \frac{1}{j\,\omega\,\mu_f} \nabla\nabla' G_\psi^{(fs)}, \tag{3}$$

where $\bar{G}_E^{(fs)}$ is the electric field dyadic Green's function of a multilayer sphere presented in [12]. The primed and unprimed coordinates and subscripts s and f refer to source and field quantities, respectively.

If the source region is segmented by linear triangles, unknown current coefficients in the antenna can be determined by applying RWG basis functions and satisfying the boundary conditions. Since tangential component of electric field vanishes on perfect conducting metal, impedance matrix is formulated as follows:

$$Z_{pq} = -\iint_{s}\iint_{s'} \begin{bmatrix} j\omega\, f_p(\mathbf{r}).\overline{\mathbf{G}}_A.f_q(\mathbf{r}') \\ +\left(\nabla.f_p(\mathbf{r})\right) G_\psi \left(\overrightarrow{\nabla}'.f_q(\mathbf{r}')\right) \end{bmatrix} ds'\, ds, \qquad (4)$$

Where $\bar{G}_A$ and G_ψ are magnetic potential DGF and electric scalar Green's function, respectively. Galerkin's method is applied for test functions and the integration over the testing triangles can be avoided by using the centers of field triangles and approximate Galerkin's method [11]. Typically, in solving integral equations by MoM, integrating over segmented cells takes about 90% of computation volume. The Gaussian quadrature method can be used for integration over source triangles in RWG method. Applying 3-point Gauss quadrature is sufficient for this integration. Regarding Fig. 1, in order to obtain the impedance matrix of MoM, all interactions between source triangles (s=1,2) and field triangles (f=1,2) should be considered.

2.2 Asymptotic Method for Spherical DGFs

By using wave transformations, some solutions of the wave equation in various coordinates can be approximated by specific functions. Associated Legendre and Hankel transforms are used widely in spherical coordinates as mentioned in details in [15]. In a multilayer sphere, asymptotic approximations of the electric DGFs between layers can be used instead of using conventional forms of DGFs. As all interactions between current elements should be considered in computation of the MoM impedance matrix, asymptotic DGFs between layers as well as those on layers f=s=i are required. In this paper, i can be 1 or 2 regarding microstrip patch and parasitic element positions shown in Fig. 1. Asymptotic formulation related to a four-layer sphere is presented as follows:

$$\overline{\mathbf{G}}_A^{(fs)}\Big|_a = \begin{cases} g^{(f)}\overline{\mathbf{I}} & ;\ f = s \\ 0 & ;\ f \neq s \end{cases}, \qquad (5a)$$

$$G_\psi^{(11)}\Big|_a = \frac{-j\omega\mu}{4\pi k_1^2}\left(\frac{e^{-jk_1R}}{R} - \left(g_1+g_2+g_3\right)\right), \qquad (5b)$$

$$G_\psi^{(12)}\Big|_a = \frac{j\omega\mu}{4\pi k_1 k_2} t_1 \left(\frac{e^{-jk_2R}}{R} - g_2 - g_3\right), \qquad (5c)$$

$$G_\psi^{(21)}\Big|_a = \frac{j\omega\mu}{4\pi k_1 k_2}\frac{1}{t_1}\left(\left(1-w_1^2\right)\frac{e^{-jk_1R}}{R} - g_2 - g_3\right), \qquad (5d)$$

$$G_\psi^{(22)}\Big|_a = \frac{-j\omega\mu}{4\pi k_2^2}\left(\frac{e^{-jk_2R}}{R} + \left(g_1-g_2-g_3\right)\right), \qquad (5e)$$

$$g^{(f)} = \frac{e^{-jk_fR}}{R}, \qquad (5f)$$

$$g_i = w_i \frac{a_i}{r}\frac{e^{-jk_iR_i}}{R_i}, \qquad (5g)$$

$$w_i = \frac{\varepsilon_i - \varepsilon_{i+1}}{\varepsilon_i + \varepsilon_{i+1}}, \qquad (5h)$$

$$t_i = \frac{2\sqrt{\varepsilon_i\,\varepsilon_{i+1}}}{\varepsilon_i + \varepsilon_{i+1}}, \qquad (5i)$$

$$R = \left|r - r'\right|;\ R_i = \sqrt{r'^2 + d_i^2 - 2r'd_i\cos\gamma}, \qquad (5j)$$

$$\cos\gamma = \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\varphi-\varphi'), \qquad (5k)$$

Where $d_t = a_t^2/r$ and $\bar{I}$ is the unit dyad.

Therefore, the input impedance of an antenna located on a multilayer sphere can be obtained using DGF or asymptotic approximation methods. Although asymptotic approximation method yields a higher convergence speed in antenna input impedance calculation, it cannot be utilized for radiation pattern determination since field and source points are not at the same distance from the sphere center. It should be mentioned that the proposed antenna can also be simulated with commercial softwares. However, simulator packages are highly dependent on meshing the structure, modeling the probe and size of radiation box. Therefore, more time and memory is required to obtain precise and stable results from simulator packages. Due to fast computation speed of the presented method, it is very efficient for the analysis of various spherical antennas.

2.3 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. 2 (a), current components to be considered are J_φ and J_θ which are in harmony with spherical components of DGFs [12]. However curvilinear meshing is complicated as compared with linear triangular meshing considered in this paper.

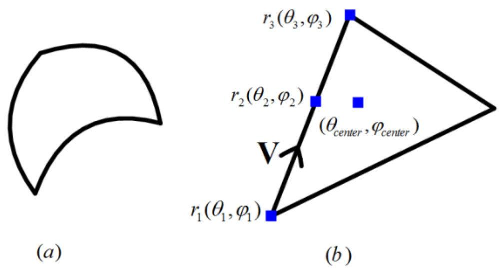


Fig.2. (a) Curvilinear triangle, (b) Linear triangle.

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 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 $\mathbf{V}$ shown in Fig. 2(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:

$$\mathbf{E}^{(Cartesian)} = -j\omega\mu_f \iint_{s'} \overline{\mathbf{G}}^{(Cartesian)} . \mathbf{J}^{(Cartesian)}(\mathbf{r}')\, ds' \tag{6}$$

Thus by using triangular linear meshes in Cartesian coordinates only $\overline{\mathrm{G}}$ 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 $\hat{r}\hat{\theta}$ component of a dyad is extracted as follows:

$$\hat{r}\hat{\theta} = (\sin\theta_f \cos\varphi_f\ \hat{x} + \sin\theta_f \sin\varphi_f\ \hat{y} + \cos\theta_f\ \hat{z})$$
$$(\cos\theta_s \cos\varphi_s\ \hat{x} + \cos\theta_s \sin\varphi_s\ \hat{y} - \sin\theta_s\ \hat{z}), \tag{7}$$

which 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. It should be noted that the proposed antenna can be simulated with commercial 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.

3. Results

In order to validate the proposed method, a prototype of a spherical probe-fed microstrip patch antenna is implemented and tested. The antenna dimensions are given in Table I. The PEC spherical shell consists of two hemispheres constructed by a CNC instrument. Two holes are cut on two sides of the sphere to pass the coaxial cable through the sphere and connect the inner conductor of the cable to the microstrip patch. The structure can also be tested with only one hemisphere above a planar perfect ground structure. The antenna is excited by a 20cm RG-58U coaxial cable of 50Ω characteristic impedance. The cable is connected to the microstrip patch at 1cm distance from the center of the patch. The circular patch antenna has been made from a RT/duroid 5870 substrate of 0.8mm thickness and dielectric constant of 2.33. A circular parasitic element is located above the patch by using a spacer material of unit relative permittivity. Figure 3 illustrates the fabricated antenna.

Table 1: Dimensions of the Probe-Fed Spherical Antenna

PEC sphere radius	5 cm
Layer 2 (εr=1) thickness	20 mm
Layer 3 (εr=2.33) thickness	0.8 mm
Conformal Patch Antenna	$0^\circ < \theta_{Patch} < 20.3^\circ$
Parasitic Element	$0^\circ < \theta_{Parasitic} < 7^\circ$

The parasitic element has been divided to 36 triangles yielding 48 common edges between plus and minus triangles and the conformal patch has been segmented into 104 triangles leading to 145 common edges. The probe is meshed into 4 triangles. Hence, there are 198 basis functions used in the MoM. In the computation of input impedance, as source triangles are near field triangles, at least 70 terms of spherical harmonics series should be considered in electric scalar Green's function to obtain a good solution. On the other hand, considering the first 20 terms of spherical harmonics is sufficient to obtain radiation patterns of about 2% error. Figure 3 illustrates the return loss of the antenna with and without the parasitic stack. The input impedance/admittance of antenna depends on current distribution of source elements in the antenna and this fact comes from the integration method in conjunction with MPIE formulation.

As it can be noticed, using the parasitic element yields a better return loss and increases the return loss bandwidth. As illustrated in Fig. 4, there is good agreement between the results obtained from measurement, asymptotic approach and DGF method.

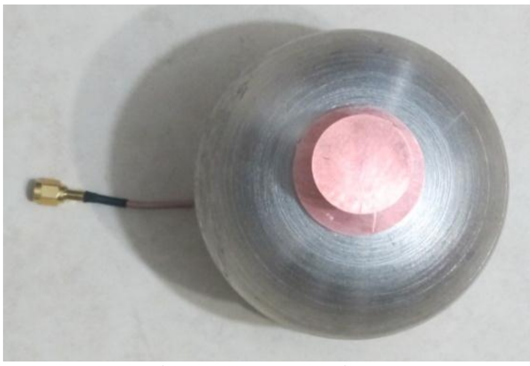


Fig. 3 Prototype of the spherical probe-fed microstrip antenna

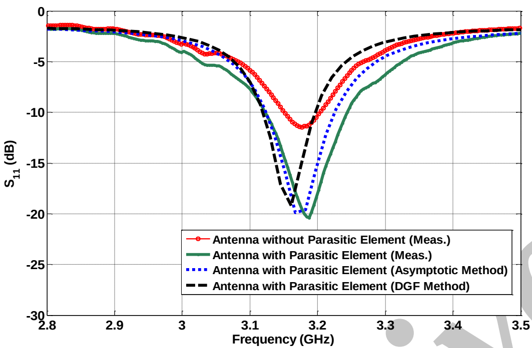
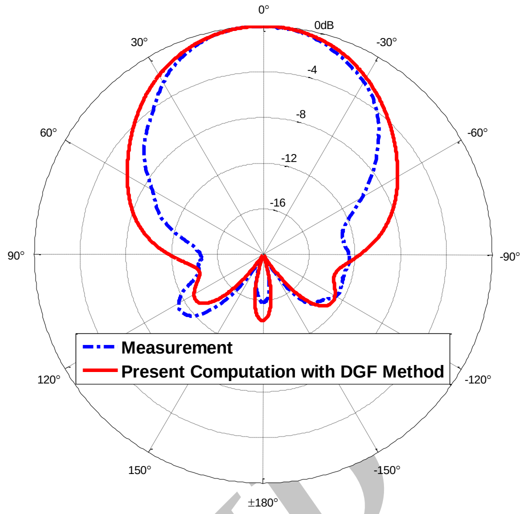


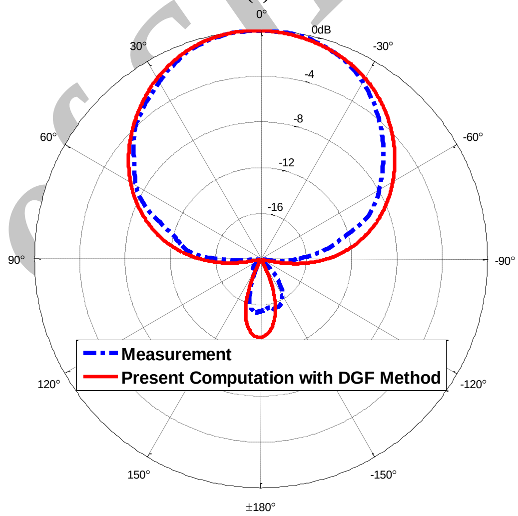
Fig. 4. Computed and measured return loss of the spherical multilayer probe-fed antenna.

Fig. 5 demonstrates the radiation patterns of the spherical probe-fed antenna at 3.15 GHz with parasitic element obtained from analytical solution and the measurement of the antenna. As it can be noticed, good agreement between the results is achieved. The difference is due to the probe inductive reactance, partial dielectric over the PEC sphere and fabrication tolerance. Typically, a matching circuit should be designed for a spherical aperture-coupled antenna to match the input impedance of the antenna to a 50Ω load. In the presented method, it takes about 8 minutes to compute E- or H-planes radiation patterns (with 60 divisions of θ) with a Core 2 Quad @ 2.86 GHz processor. The fast computation time of this method is considerable in comparison with CAD simulator packages and is very efficient for analysis of spherical antennas.

Figure 6 illustrates the measured radiation patterns with and without the parasitic element. It is observed that the stack increases the antenna directivity and decreases side lobes levels in the radiation patterns.



(a)



(b)

Fig. 5 Radiation patterns of the spherical probe-fed antenna at 3.15 GHz with parasitic element; (a) E-Plane, (b) H-Plane.

As shown in Fig. 6, parasitic element makes antenna radiation patterns more directive but it increases cross polarization radiations. The latter is because of electromagnetic fields perturbation due to the existence of parasitic element.

The antenna efficiency is measured by a Bluetest reverberation chamber setup and is about 86% and 83% at 3.1GHz and 3.2GHz, respectively. A standard antenna is used to measure the gain of the antenna with and without the parasitic element. Table II shows the antenna gain at different frequencies. It is noticed that the gain of the antenna is increased with the presence of the parasitic element.

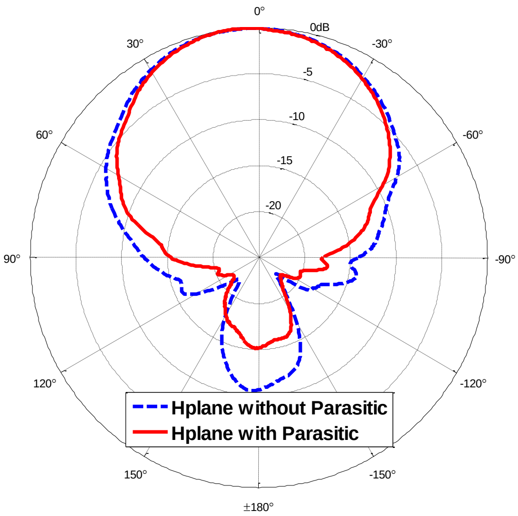


Fig. 6 H-Plane radiation patterns of the spherical probe-fed antenna with and without parasitic elements at f=3.2GHz.

Table 2:
Measured Gain of the Spherical Probe-Fed Antenna

Frequency (GHz)	Gain Without Parasitic Element (dB)	Gain With Parasitic Element (dB)
2.95	3.45	4.31
3.05	5.3	5.9
3.15	6.05	6.9
3.25	1.15	2.32

4. Conclusion

Full-wave analysis of a probe-fed microstrip antenna with a conformal parasitic element mounted on a three-layer spherical structure has been presented in this paper. Green's functions required in MPIE formulation have been extracted. The antenna has been analyzed by using linear triangular cells and by modeling the coaxial probe. Near and far fields of the antenna have been calculated resulting in computation of the input impedance and radiation patterns of the antenna, respectively. To validate the present computation, a spherical probe-fed microstrip antenna has been implemented and tested. Robustness and accuracy of the proposed method have been verified by comparing the results of our method with those of the measurement. The parasitic element improves the antenna characteristics such as input impedance, gain and radiation patterns.

Acknowledgements

The authors would like to thank the K. N. Toosi University Wireless Test Lab. for the measurement of the antenna efficiency.

References

[1] C. T. Tai, *Dyadic Green's Functions in Electromagnetics Theory*, New York: IEEE Press, 1994.

[2] W. C. Chew, *Waves and Fields in Inhomogeneous Media*, New York: IEEE Press, 1995.

[3] A. Fallahi and B. Oswald, "On the computation of electromagnetic dyadic Green's function in spherically multilayered media," *IEEE Trans. Microwave Theory Tech*., vol. MTT-59, no. 6, pp. 1433–1440, Jun. 2011.

[4] Javad. S. Meiguni, M. Kamyab, and A. Hosseinbeig, "Theory and experiment of spherical aperture-coupled antennas," *IEEE Trans. Antennas Propagat*., vol. 61, no. 05, pp. 2397-2403, May 2013.

[5] Javad. S. Meiguni, M. Kamyab, and A. Hosseinbeig, "Spherical Aperture-Coupled Antennas with Parasitic Element," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 27, no. 12, pp. 999-1006, Dec. 2012.

[6] Z. Sipus, N. Burum, and J. Bartolic1, "Analysis of rectangular microstrip patch antennas on spherical structures," *Microw. Opt. Technol. Lett*., vol. 36, issue 4, pp. 276–280, Feb. 2003.

[7] T. Fortakia, L. Djouaneb, F. Chebarab & A. Benghalia, "Radiation of a rectangular microstrip patch antenna covered with a dielectric layer," *International Journal of Electronics*, vol.95, issue 9, pp. 989-998, 2008.

[8] J.P. Damiano and A. Papiernik, "Survey of analytical and numerical models for probe-fed microstrip antennas," *IEE Proc.-Microw. Antennas Propag*., Vol. 141, no. I, pp. 15–21, February 1994.

[9] M. He, Q. Chen, Q. Yuan, K. Sawaya , X. Xu, "A Simple Strip Model in the Volume-Surface Integral Equation for Analysis of Arbitrary Probe-Fed Conformal Microstrip Antennas," *IEEE Antennas and wireless propag Letter*, vol. 8, pp. 530–533, Feb. 2009.

[10] A. Hosseinbeig, M. Kamyab, and Javad. S. Meiguni, "Theory of aperture-coupled hemispherical dielectric resonator antennas with radiating elements," *International Journal of Electronics and Communications (AEU)*, Available online 31 May 2013.

[11] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antennas Propag*., vol. 30, pp. 409–418, May 1982.

[12] L.W. Li, P. S. Kooi, M. S. Leong, and T. S. Yeo, "Electromagnetic dyadic Green's function in spherically multilayered media," *IEEE Trans. Microwave Theory Tech*., vol. 42, pp. 2302-2310, Dec. 1994.

[13] R. F.Harrington, *Field Computation by Moment Methods*, IEEE press series in Electromagnetic Waves, 1991.

[14] W. C. Gibson, *The Method of Moments in Electromagnetics*, Chapman & Hall/CRC, Taylor & Francis Group, 2008.
[15] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*, IEEE press, John Wiley & Sons inc., 2001.
[16] S. K. Khamas, "Asymptotic extraction approach for antennas in a multilayered spherical media," *IEEE Trans. Antennas Propag*., vol. 58, no. 3, pp. 1003–1008, Mar. 2010.

Javad Soleiman Meiguni was born in 1982 in Tehran, Iran. He received his B.S. from Semnan University, Semnan, Iran and M.S. from K. N. Toosi University of Technology, Tehran, Iran in 2005 and 2008, respectively all in Electrical Engineering. He received his Ph.D. in telecommunications at K. N. Toosi University of Technology, Tehran, Iran. Currently, he is an assistant professor at the faculty of electrical and computer engineering in Semnan University. He has participated in many projects inside and outside the university. His research is mainly focused on the areas of antennas and EM modeling, numerical techniques in electromagnetics by using dyadic Green's functions, antenna design and measurement, active and passive microwave and millimeter-wave circuit design. During his PhD. studies he has published 6 ISI papers (including IEEE Transactions on Antenna and Propagation journal, Applied Computational Electromagnetic Society (ACES) journal, Electromagnetics journal, International Journal of Electronics and Communications (AEU) and ELEX journal), 3 scientific research papers and 3 papers in conference proceeding.

Manouchehr Kamyab received the B.S. and M.S. from the University of Tehran, Tehran, Iran, and the PhD degree from Michigan State University, in 1982, in electrical engineering. His research interest includes the metamaterials and their applications in antenna engineering, electrically small antennas, microwave and millimeter-wave circuits, and mobile communication systems. He was a professor in the Department of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran. Dr. Kamyab has been leading a group of graduate students in the areas of negative-refraction metamaterials and their microwave applications, integrated antennas and components for broad-band wireless telecommunications, novel antenna beam-steering techniques, millimeter and sub-millimeter-wave circuits, as well as scattering and inverse scattering problems.

Ahmad Hosseinbeig was born in 1983 in Tehran, Iran. He received the B.S. in electrical engineering from Shahid Bahonar University, Kerman, Iran and M.S. in telecommunications engineering from K. N. Toosi University of Technology, Tehran, Iran in 2006 and 2008, respectively. He received his Ph.D. in telecommunications engineering at K. N. Toosi University of Technology, Tehran, Iran. His main area of interest is numerical techniques in electromagnetic theory, analysis and design of spherical aperture-coupled Dielectric Resonator Antennas (DRA) using DGFs, antenna design and measurement, microwave and high frequency circuit design.