Design and Analysis of Planer, Single Feed, Four-Band Microstrip Antenna Operating in the Same Polarization Plane

Falih M. Alnahwi, Mohammad S. Zidan, and Naz E. Islam, *Senior Member*, IEEE

Abstract—The design and analysis of a single compact antenna, that can operate at Global System for Mobile (GSM), Mobile Satellite Service (MSS), Industrial Scientific Medical (ISM), and Fixed Satellite Service (FSS) frequencies is presented. The design is based on the utilization of a chip resistor to split the two frequency bands of the step-slotted patch antenna into four frequency bands. The four frequency bands that are generated by the proposed antenna are all in the same polarization plane. The proposed antenna is easy to fabricate and is expected to be used in modern communication devices to replace multi antennas to handle different frequency bands. The analysis of the antenna is done by using an in house FDTD code to provide an in-depth study of the physics of the radiation mechanism. Results from the code were validated through commercial simulation suit and are in good agreement. Some discrepancy in the return loss appears to be due to the mesh generation methodology implemented in each code.

Index Terms—Four band antenna, Chip Resistor, Finite Difference Time Domain, Planar Patch Antenna, Return Loss.

1 Introduction

THEmicrostrip antennas occupy a niche of their own in the modern day communications systems such as cell phone, satellite radio, space craft, and other gadgets. Its relative advantages include small size, low cost, and ease in fabrication [1]. In recent years, an area of research focus is in the design study of a single multiband microstrip antenna that can potentially be used in systems that utilize multiple frequencies. Such an antenna would optimize materials, real state, and time and thus will be cost effective.

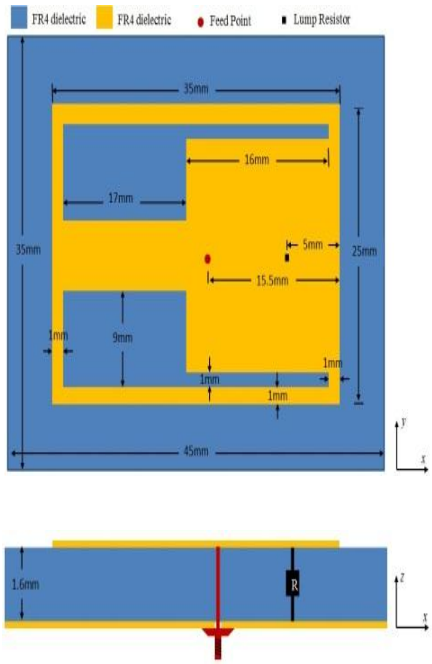
Two band antenna study include a two T-match stub that operates in the Bluetooth and IEEE802.11a bands [2],a patch antenna with aperture feed to operate at UHF and GSM/CDMA bands [3], a double band stacked antenna with circular polarization for satellite navigation system [4], and a two port feed dual polarization patch antenna that operates at PCS and ISM frequency bands [5]. Reported three band antenna include three overlapped patches for WLAN applications [6], a double layer microstrip antenna with two U-slots and conventional coaxial feed [7], a directional triple band planer antenna based on the concept of the dipole antenna for WLAN/WiMax applications [8], triple band antenna with h-slot embedded in the center of the patch [9], a stacked antenna with circular polarization for use in GPS receivers [10], a compact printed antenna for WLAN/WiMax applications [11], and a body-worn antenna for GSM/PCS/WLAN communications [12].

In the design of four band antennas, few attempts have been successful. For example, in 2013, Karimian et al. [13]designed a four port F-shaped quad-band patch antenna for WLAN/WiMax multi-input multi-output systems. We have also designed a four band planer patch antenna with radiation pattern not in the broad side direction [14]. All the reported designs, however, use double layer, complex design, multi feed points, or imperfect radiation characteristics to produce multi bands for specific applications.

In this paper, we propose a compact and low profile, single feed microstrip antenna that is not only planar in design, but can generate four useful frequency bands in the same polarization plane. Unlike the stacked antenna, the proposed antenna has a low profile and will be easy to fabricate. In addition this antenna is compact in size as compared to the conventional microstrip antenna used in GSM applications. The study shows that the proposed antenna can be utilized in Global System for Mobile GSM, Mobile Satellite Service MSS, Industrial Scientific Medical ISM, and Fixed Satellite Service FSS applications. Following this brief introduction, the rest of the paper is organized as follows: The proposed antenna is discussed in Section 2, while the simulation method used in the analysis of the proposed antenna is explained in Section 3. The simulation results and a comparison between the simulation results and those of an industry standard simulation suite are shown in Section 4. Section 5 describes the physical effect of inserting chip resistor inside the patch antenna. Finally, Section 6 concludes with a brief summary.

2 Antenna Structure

Fig. 1 illustrates the top and the side view of the proposed antenna. It has a copper patch ($\sigma = 5.7 \times 10^7 mho/m$) of length $L = 35\ mm$ and width $W = 25\ mm$. The ground plane is also made of copper with $L^{'} = 45\ mm$ and width $W^{'} = 35\ mm$. The substrate dielectric is FR4 ($\varepsilon_r = 4.3,\ \mu_r = 1, \sigma = 0.025\ mho/m$) with the same length and width as the ground plane and height $h = 1.6\,mm$. Two step slots are embedded on the surface of the patch along its length and shifted $1\,mm$ away from the patch edges. The narrower side of the step slot is $1\,mm$ while the wider side is $9\,mm$ in width. As reported elsewhere, these two slots make the antenna operate at dual frequency bands [15]. A $1\,\Omega$ chip resistor (lump resistor) is inserted through the ground plane via a small hole and connected to the patch and the ground plane. As will be shown later in Section V, this resistor effectively reduces the antenna size, splits each frequency band into two bands, and increases the band width of each band. An important feature of this design is that a single coaxial feed point is located in the middle of the width in order to prevent any radiation toward the width and keeps the radiation to be in one polarization plane only. The selection of the position of the feed point is an important part of the design and must be done with precision in order to achieve good matching for all the four frequency bands.



(a)

(b)

Fig. 1. The structure of the four-band antenna (a) Top view and (b) Side view.

3 In-House Code

The simulation of the proposed antenna is based on a developed in-house code to simulate the Finite Difference Time Domain (FDTD) method [15]. The results are compared with those of an industrial simulation suite (CST Microwave Studio) in order to validate the accuracy of the in-house code. The use of the in-house code is necessary to analyze the physics of the designed antenna, which is otherwise not available through the commercial simulation suite.

For the FDTD based code, the Yee cell dimensions are $\Delta x = 1\,mm, \Delta y = 0.5\,mm$, and$\Delta z = 0.533\,mm$. Therefore the total mesh dimensions are $45 \times 70 \times 3$ cells in x, y, and z directions, respectively. The antenna is excited at its feed point using a voltage source having internal resistance of $50\,\Omega$. A Gaussian pulse with accuracy parameter equal to $(n_c = 20\, cell\ per\ wavelength)$ is selected to be the source waveform, and is given by (1):

$$g(t) = e^{-(t-t_o/\tau)^2} \quad (1)$$

wheret_o represents a specific time shift, and τ denotes the pulse width. These two parameters have optimum values given by (2) and (3), respectively [16]:

$$t_o \cong 4.5\tau \qquad (2)$$

$$\tau \cong \frac{max(\Delta x, \Delta y, \Delta z) \times n_c}{2c} \qquad (3)$$

where$c$ denotes the speed of light in freespace, and max denotes the maximum value. After applying the above two equations, the value of t_o and τ are found to be $150\,ps$ and $33.33\,ps$, respectively. A suitable time step Δt was determined from (4) to ensure the stability of the FDTD processing [15]:

$$\Delta t = 0.9\frac{1}{c\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \qquad (4)$$

The value of the time step is found to be $1.3\,ps$.

A perfectly absorbing boundary condition has been applied to the simulation structure surrounding the antenna with 10 *cells* air buffer followed by 8 *cells* Convolutional Perfect Matched Layer (CPML) [15]. The CPML ensures that no field component is reflecting back to the antenna. This is evident from Fig. 2 and Fig. 3 which show the electric and magnetic fields distribution, respectively, at different time instants. It is clear that the magnetic and electric fields are zero at the boundary which means that there is no field reflects back to the problem space:

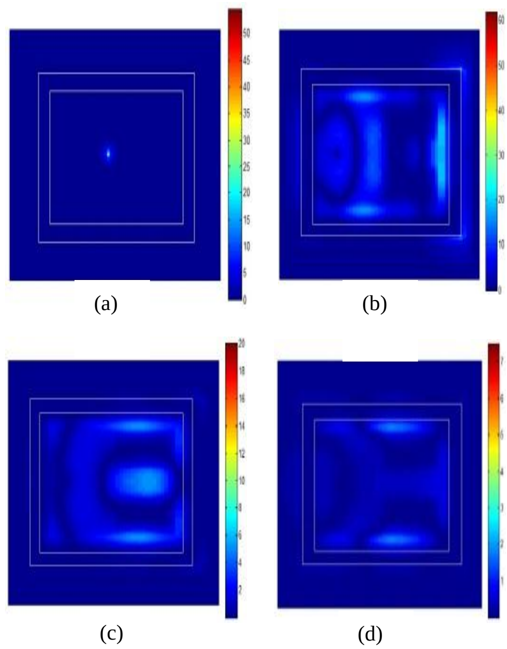


Fig. 2. Distribution of the electric field at (a) $100\Delta t$, (b) $1000\Delta t$, (c) $3000\Delta t$, (d) $5000\Delta t$.

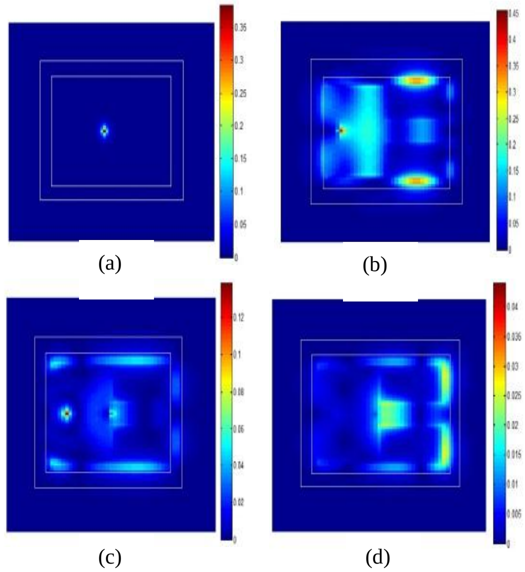


Figure 3. Distribution of the magnetic field at (a) 100Δt, (b) 1000Δt, (c) 3000Δt, (d) 5000Δt.

4 Results and Discussion

Fig. 4 shows the return losses of the proposed four band antenna that is calculated using the in-house code. This figure clearly demonstrates the four frequency bands which have return loss less than -10dB , and thus are useful frequencies. The first band is centered at 850MHz in the GSM band. The second band is centered at 2GHz which is used for mobile satellite service MSS. The third one is centered at 2.4GHz for ISM applications while the last band is centered at 4GHz which is used for fixed satellite service FSS. The return losses at each resonant frequency are -15.8dB, -15.75dB, -18dB, and -19.4dB, respectively. Table 1 gives the bandwidth around each resonant frequency which is calculated at $|S_{11}|\leq 10$dB. There is a noticeable bandwidth enhancement compared to the conventional microstrip antenna due to the effect of the chip resistor.

TABLE1
The Resonant Frequencies And Their Corresponding Return Loss

Band	f_c (GHz)	f_L (GHz)	f_H (GHz)	10dB BW (MHz, %)
1	0.85	0.81	0.91	100, 11.6
2	2	1.98	2.061	81, 4.1
3	2.4	2.39	2.48	90, 3.8
4	4	3.9	4.1	200, 5

The radiation patterns corresponding to each resonant frequency are shown in Fig. 5. The first frequency band gives approximately isotropic radiation pattern while all the other resonant frequencies give good broadside characteristics. In general, the radiation characteristics of the proposed antenna are reasonable and suitable for the wireless applications because of these convenient

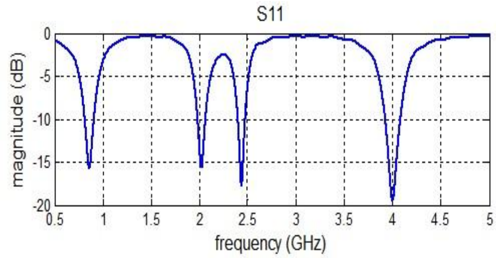


Fig. 4. The return losses of the proposed four band antenna.

broadside radiation characteristics. It is clear from Fig. 7 that the proposed antenna has a very good broad side radiation. Furthermore, the cross polarization is small especially for the E-plane which approaches zero.

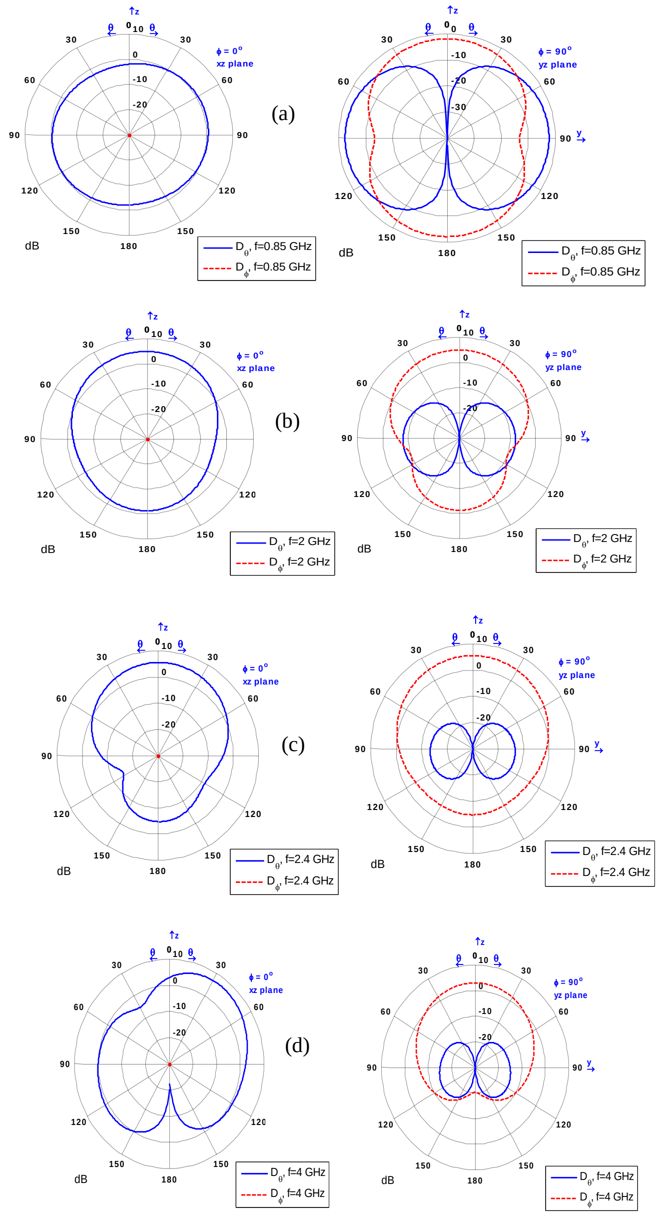


Fig. 5. The directivity pattern of the proposed antenna at the E-plane plane (xz plane) and the H-plane (yz plane) at (a) 0.85GHz, (b) 2GHz, (c) 2.4GHz, (d) 4GHz.

The return losses are compared to that of a commercial simulation suite called CST Microwave Studio. Fig. 6 shows the resulted return losses, which includes the four frequency band for the antenna. Comparisons of the return losses show minor deviation between the two results. This deviation could be attributed to the incorporation of dynamic mesh size in the commercial code, where the mesh size can automatically change the number of Yee cells at different locations for better convergence while this is not viable in the in-house code. In spite of this difference, the return losses of the commercial software still gives frequencies at GSM, MSS, ISM, and FSS frequency bands which is also evident in the in-house code results. However, the in-house program is more flexible because some unwanted parameters can be removed from the calculations, which significantly improves the speed of the program. In addition, specific antenna parameters can be added to the code to provide additional physical interpretations for the antenna design.

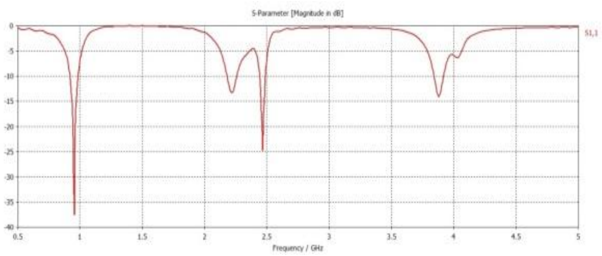


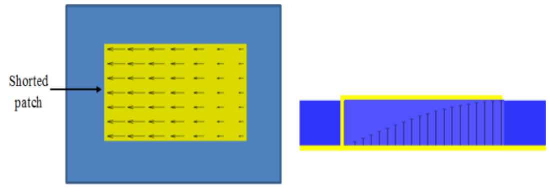
Fig. 6. The return losses of the four band antenna using CST Microwave Studio.

The validated in-house code can be used to analyze the effect of the chip resistor on the designed four band antenna.

5 Physical Effects of the Chip Resistor

In order to analyze the effects of chip resistor the in-house code described earlier was used. It can be shown that the chip resistor (Lump Resistor) insertion through the substrate can significantly i) reduce the antenna size, ii) generate additional bands, and iii) improve the bandwidth of the antenna. Since they are independent of each other, these three figures of merit will be discussed separately.

i) Antenna Size Reduction: We begin with the analysis of a shorted patch antenna (the chip resistor is a special case of this shorted antenna where the current and voltage paths are controlled by the chip dimensions).Fig. 7 shows the current distribution (7(a), top view) and the voltage distribution (7(b), side view) of the shorted patch antenna, which has one side of its patch connected directly to the ground plane. The current of the first resonant mode is zero at the open side of the patch and increases as it moves to the shorted side (Fig. 7(a)) and vice versa for the voltage distribution. This suggests that the antenna resonates at quarter wavelength ($\lambda/4$) instead of half wavelength at which the conventional un-shorted antenna resonates. As a result, this leads to a reduction in the antenna size by half for the same resonant frequency and thus the resonant mode is ($0.5f_{10}$).



(a) (b)

Fig. 7. A shorted patch antenna (a) Top view: current distribution and (b) Side view: voltage distribution.

Fig. 8 shows the current distribution of an antenna loaded by a chip resistor. The voltage distribution (not shown) is similar to that of the shorted antenna. Insertion of a chip resistor can be treated as a special case of the shorted antenna described earlier. Here only a small area of the patch is shorted through a low value resistor. Since the current in this case, which converges towards the chip resistor, takes a longer path (curved path as shown in Fig. 10) to reach the shorted point, the size of the antenna undergoes further reduction compared to the shorted patch antenna and the resulting antenna will resonate at a frequency less than $0.5f_{10}$.

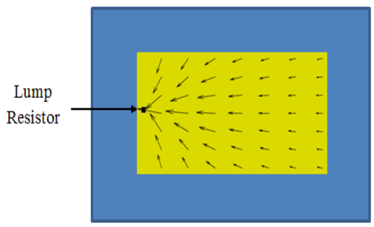


Fig. 8. The current distribution of a patch antenna loaded by chip resistor.

ii) Generation of Extra band: The voltage distributions of the shorted patch show that there is higher mode at which the antenna can resonate. At ($1.5f_{10}$) the voltage distribution is also zero at the shorted edge and maximum at the open edge. Fig. 9 illustrates the voltage distribution of $1.5f_{10}$ mode which considered the second resonant mode of the shorted and the resistor loaded patch antenna.

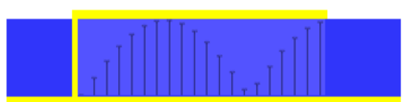


Fig. 9. The second resonant mode voltage distribution of a shorted patch antenna.

iii) Bandwidth Enhancement: Chip resistor can reduce the quality factor of the antenna because the resistance increases the losses of the dielectric material. Therefore, the bandwidth of the resulted antenna is widened. Although increasing the value of the chip resistor leads to wider bandwidth, it also increases the losses of the antenna which leads to a reduction in gain. For this reason, the antenna analyzed here has a chip resistor of 1 Ω, thereby improving the bandwidth without adding much loss to the antenna.

It is worthwhile to mention that changing the position of the chip resistor shifts the resonant frequency of the antenna [15]. This suggests that another set of four band antenna can be obtained by controlling the parameters of the chip resistors. However the feed point must be readjusted to match the new distributed impedance.

6 Conclusion

Due to the ever increasing demand in electronic devices that can operate at different frequency bands, multiband antennas design is at the forefront of research for antenna design studies. Gadgets that utilize multiple antennas for each frequency of operation do consume resources, real state and would not be cost effective. Dual, triple, and even four band antennas have been designed in the recent years, but most of them use multi layers, complex design, or multi feed to generate multiple bands that operate for different applications.

This work proposes and analyzes a single feed patch antenna that can operate at four different frequency bands in the same polarization plane. This antenna has application in GSM, MSS, ISM, and FSS devices. The proposed design is based on inserting chip resistor to a step slot patch antenna to generate four bands instead of two, compact the antenna size, and enhance the antenna bandwidth. This antenna also has good broadside radiation characteristics that are accommodate the wireless applications. The development and analysis through in-house developed code provides greater flexibility in defining the physics of the radiation mechanism which may not be possible through a commercial code.

References

[1] C. Balanis, Antenna Theory: Analysis and Design, 3rd Ed., John Wiley &Sones, INC: New York, 2005.

[2] Y. Lin, and K. Hung, "Design of Dual Band Slot Antenna with Double T-match Stubs," *Electronics Letters*, vol. 42, no. 8, Apr. 13th, 2006.

[3] Z. Xu and X. Li, "Aperture Coupling Two-Layered Dual-Band RFID Reader Antenna Design," *IEEE International Conference on Microwave and Millimeter Wave Technology*, pp. 1218-1221, 2008.

[4] M. Chufarov, L. Livova, and A. Babushkin, "Double-Band Circularly-Polarized Antenna for GLONASS-GPS Applications," *IEEE European Conference*, pp. 14-19, 2009.

[5] V. Nimbark, QLu, E. Korolkiewicz, and L. Liu, "Design of a Three Port Feed Matching Network for a Dual-Band Dual-Polarized Rectangular Patch Antenna," *IEEE international Conference on Signal Processing and Communications*, pp. 1-5, 2012.

[6] N. Abdulhussein, A. Abdullah, and A. Salman, "3-D FDTD Design and Analysis of a Three-Band Composite Microstrip Patch Antenna for Wireless Communication Applications," *IEEE 2nd International conference on Next Generation Information Technology*, pp. 104-108, 2011.

[7] K. Lee, K. Luk, K. Mak, and S. Yang, "On the Use of U-Slots in the Design of Dual- and Triple-Band Patch antennas," *IEEE Antennas and Propagation Magazine*, vol. 53, no. 3, pp. 60-74, Jun. 2011.

[8] R. Li, X. Quan, Y. Cui, and M. Tentzeris, "Directional Triple-Band Planer Antenna for WLAN/WiMax Access Points," *Electronics Letters*, vol. 48, no. 6, Mar. 15th, 2012.

[9] O. Noori, J. Chebil, S. Khan, M. Habaebi, M. Islam, and Saeed, "Design and Analysis of Triple-Band Microstrip Patch Antenna with h-Shaped Slot," *International Conference on Computer and Communication Engineering*, pp. 441-445, Jul. 3-5, 2012.

[10] O. L. Falade, M. U. Rahman, X. Chen, and C. G. Parini, "Single Feed Stacked Patch Circular Polarized Antenna for Triple Band GPS Receivers," *IEEE transactions on Antennas and Propagations*, vol. 60, no. 10, pp. 4479-4484, Oct. 2012.

[11] H. Zhai, Z. Ma, Y Han, and C. Liang, "A Compact Printed Antenna for Triple-Band WLAN/WiMax Applications,"*IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 65-68, 2013.

[12] Z. Wang, L. Lee, D. Psychoudakis, and J. Volakis, "Embroidered Multiband Body-Worn Antenna for GSM/PCS/WLAN Communications," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 6, pp. 3321-3329, Jun. 2014.

[13] R. Karimian, H. Oraizi, S. Fakhte, and M. Farahani, "Novel F-Shape Quad-Band Printed Slot Antenna for WLAN and WiMax MIMO Systems," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 405-408, 2013.

[14] F. M. Alnahwi, and N. E. Islam, "Four-Band Planar Patch Antenna for Digital Audio Broadcasting, Universal Mobile Telecommunications, and WiMax Frequency Signal Integration," *Canadian Journal on Electrical and Electronics Engineering*, vol. 3, no. 10, Dec. 2012.

[15] K. L. Wong, Compact and Broadband Microstrip Antennas, John Wiley & Sons, INC, 2002.

[16] A. Elsherbeni, and V. Demir, The Finite Difference Time Domain Method for Electromagnetics with MATLAB Simulation, Scientech Publishing, INC, 2009.