A FREQUENCY SELECTIVE SURFACE LOADED HIGH GAIN SLANT ANTENNA FOR 2.45 GHZ RECTENNA APPLICATIONS

UDAYABHASKAR PATTAPU, SUSHRUT DAS

Key words: Defected ground structure (DGS), Frequency selective surface (FSS), Rectenna, Slant antenna, Stubs.

This paper presents a 2.45 GHz ground slot backed harmonic rejection slant antenna for wireless power transfer applications. The harmonic responses have been suppressed by using two stubs and a U-shaped ground slot. The antenna provides 3.1 dBi gain at 2.45 GHz. To improve the gain, a 2.45 GHz reflective frequency selective surface has been placed below the ground plane at an optimized distance of $0.12 \lambda_0$. After placing the FSS, antenna gain has been increased to 7.57 dBi without affecting the return loss characteristic. The antenna has been fabricated and the simulation results are experimentally verified.

1. INTRODUCTION

Present day wireless power transfer (WPT) systems require efficient, high gain antennas as the receiving element of the rectenna circuit. Such antennas should be able to receive only the signal of intended frequency and reject others to increase the system efficiency and reduce the radiation of unintended signals that are generated at the nonlinear diodes of the rectifier circuit. To achieve this characteristic, researchers have proposed the use of harmonic rejection antennas. Since these antennas are void of harmonic response, they neither radiate the harmonics generated by the rectifier nor can receive them. Such antennas therefore enable the designer to remove the band pass filter (BPF) from the rectenna circuit, making the system compact and efficient [1, 2].

For suppressing the harmonics, different techniques can be used. One way is to use a filter at the RF front ends. However, this conflicts with the compactness of the system. The other way is to directly suppress the harmonics at the antenna terminal by modifying the antenna structure itself. To do this, different techniques have been proposed, such as use of photonic band-gap structure (PBG), hybrid PBG structure [3, 5], defected ground structure (DGS) [6–10], compact microstrip resonant cell (CMRC) [11], right angle embedded slits [12], slots [13–16] *etc*.

In this paper, a slant antenna has been proposed as the receiving element of the rectenna circuit of a 2.45 GHz wireless power transmission system. Two open stubs and a U-shaped ground slot have been used to suppress all the unnecessary 10 dB return loss bandwidths. The antenna has been studied and found that it has the capability to reject signals at least upto 10 GHz, except the required 2.45 GHz band. At the operating frequency the antenna has 3.1 dBi gain. To enhance the gain, next, an FSS structure has been designed which highly reflects signal at 2.45 GHz. The designed FSS structure then has been placed at a distance of $0.12 \lambda_0$ below the ground. It has been found that after placing FSS, the gain of the antenna has been increased to 7.57 dBi.

2. RECTANGULAR DGS BACKED SLANT ANTENNA

Base station antennas with 45° polarization are commonly called slant antennas. They involve placing one antenna element 45° to the left and the other to the right by the same angle. Such polarization scheme offers more symmetrical propagation characteristics than simple vertical or

horizontal polarization and hence is preferred in mobile communication system [17]. They are also used in commercial and military applications because they generate equal horizontal and vertical components [18]. Due to this added advantage, a planar slant antenna (Fig. 1) has been considered in the proposed work as the receiving element of the rectenna circuit. FR4 substrate of thickness 1.6 mm, relative permittivity $\varepsilon_r = 4.4$, and loss tangent tan $\delta = 0.02$ has been considered as the dielectric material. Design and optimization of the antenna have been carried out using CST Microwave studio (Version 14.0).



Fig. 1 - Planar slant antenna: a) top view; b) ground plane.

Parametric analysis of the slant antenna (Fig. 1), with respect to some important design parameters, are shown in Fig. 2. The figure reveals that the operating frequency can be tuned by varying w1, w2 and l2. In practice the structure behaves as a DGS backed asymmetric dipole and therefore the total electrical length of the antenna should be half wavelength. The frequency response of the optimized slant antenna is shown in Fig. 3. It reveals several 10 dB return loss bands that are generated due to the excitation of multiple modes in the structure. Surface current distributions of the patch at the respective bands are shown in Fig. 4.



Indian Inistitute of Technology (Indian School of Mines), Department of Electronics Engineering, Dhanbad, Jharkhand, India, E-mail: uday.pattapu@hotmail.com



Fig. 2 – Parametric analysis of the slant antenna for: a) w1; b) w2; c) l2.



Fig. 3 – Simulated frequency response of the rectangular DGS backed slant antenna.





Fig. 4 – Surface current distribution on the slant antenna at: a) 2.45; b) 3.28; c) 5.73; d) 8.14; e) 9.53 GHz.

3. SUPPRESSION OF UNNECESSRAY BANDS

The frequency response in Fig. 3 reveals that in addition to the required 2.45 GHz band there are additional pass bands at 3.28, 5.73, 8.14, and 9.53 GHz. In order to suppress these additional bands, two open stubs (of lengths s1 and s2) have been used in the feed structure and a U-shaped slot (of length $2c_{1}+c_{2}$) has been used in the ground plane (Fig. 5). These structures behave as band stop filters and remove the unwanted bands from the frequency response of the antenna. To design the antenna in Fig. 5, the stub of length s1 was first introduced in the feed line and then its characteristic was studied using parametric analysis. The result of the parametric analysis is shown in Fig. 6a. The figure reveals that as the length s1 increases, it suppresses all the bands until $s_1 = 3.8$ mm. If s_1 is further increased, the bands at 3.28 and 5.73 GHz gets suppressed by more degree, but additional bands are formed at 8.5 and 9.8 GHz (for $s_1 = 4.8$ mm). In order to suppress these bands, another stub of length s2 has been used in the feed line. The result of parametric analysis of the dual stub loaded antenna in Fig. 6b reveals that as s2 increases the new bands at 8.5 and 9.8 GHz get suppressed, keeping the frequency response up to 7 GHz unchanged. The optimized value of s2 has been chosen as 3.3 mm. Finally a U-shaped slot has been introduced on the ground plane, beneath the feed line, to fine tune the stop band frequency response. The parametric analysis of the antenna, with the U-shaped slot length (or more precisely with c1) is shown in Fig. 6c. The optimized dimensions of c1 and c2 have been kept as 3.52 mm and 4.7 mm, respectively.







Fig. 6 – Parametric analysis of the slant antenna: a) s1;b) s2; c) c1.

The proposed antenna dimensions are: Ls = 45, Ws = 50, l1 = 26.75, l2 = 16.75, w1 = 10, w2 = 6, w3 = 5, w4 = 3, h1 = 8.11, h2 = 11.85, h3 = 14.65, s1 = 4.8, s2 = 3.3, sw = 1, fe = 3.2, b1 = 24, b2 = 10, bh = 20, d = 5.7, c1 = 3.52, c2 = 4.7, $\alpha = 45^{\circ}$ (all dimensions are in mm).



Fig. 7 – Surface current distribution of the radiating patch and the ground plane at: a) 2.45; b) 4.9; c) 7.35; d) 9.8 GHz.

The band stop characteristics of the stubs can be visualized by observing the surface current distribution on the antenna at discrete frequency points, shown in Fig. 7. Based on the simulated result the antenna has been fabricated and measured. The fabricated antenna is shown in Fig. 8. The farfield measurement has been carried out using a calibrated Keysight N9926A analyzer was used to measure the received signal strength. Comparison of the simulated (CST) and measured frequency responses of the antenna is shown in Fig. 9. The simulated and measured results are in close agreement, which validates the analysis. Fig. 9 reveals a 10 dB return loss, bandwidth from 2.36 to 2.57 GHz, which is around 4.25 % on each side of the center frequency.

The gain of the antenna has been measured using two antenna method and the experimental setup is shown in Fig. 10. Simulated and measured gain responses of the antenna are plotted and compared in Fig. 11 which reveals that in the entire return loss bandwidth, gain remains almost constant around 2.6 dBi with a maximum of 3.1 dBi at 2.45 GHz and a minimum of 2.6 dBi at 2.59 GHz, respectively.



Fig. 8 - Fabricated antenna: a) top view; b) bottom view.



Fig. 9 – Comparison of the simulated and measured frequency response of the slant antenna in Fig. 5.



Fig. 10 – Experimental setup to measure the gain of an antenna.



Fig. 11 -Simulated and measured gains of the antenna in Fig. 5.

Simulated and measured co- and cross polarization radiation patterns of the proposed antenna on yz and xzplanes are plotted in Fig. 12. It can be observed that the antenna has a dipole like radiation pattern in the yz-plane and nearly omnidirectional pattern in xz-plane. The simulated beam widths of the radiation pattern at the $\Phi = 0^{\circ}$ (xz-plane) and 90° (yz-plane) are 127° and 81° respectively. The cross polarization level is more than 18 dB down than the copolarization level in the broadside direction of the antenna on both the orthogonal planes.



Fig. 12 – Simulated and measured normalized co- and cross-polarized radiation pattern on: a) *yz*-plane ($\Phi = 90^{\circ}$ and $\theta = all$); b) *xz*-plane ($\Phi = 0^{\circ}$ and $\theta = all$).

4. DESIGN OF FREQUENCY SELECTIVE SURFACE

The antenna, shown in Fig. 5, possesses a maximum gain of 3.1 dBi at 2.45 GHz. In order to enhance this gain, next, a frequency selective surface (FSS) has been used. The concept was to design an FSS that is highly reflective at 2.45 GHz and place it at an optimized distance below the ground plane so that the backscattered filed ($\theta = 180^{\circ}$) can be reflected by it and add to the broadside field ($\theta = 0^{\circ}$) at the same phase to increase the broadside gain [19].

In the proposed work an overlapped offset slot shaped structure has been considered as the unit cell of the FSS Fig. 13a. The different dimensions of the structure have been found by carrying out parametric analysis of the structure, shown in Fig. 14. For high reflection at 2.45 GHz, the optimized dimensions of the FSS unit cell are found to be d1=4 mm and d2=2 mm.



Fig. 13 – a) Proposed FSS unit cell; b) fabricated FSS structure.





Fig. 14 – Parametric analysis of unit cell of proposed FSS structure with: a) d1; b) d2.

The optimized frequency response of the FSS unit cell is shown in Fig. 15. It reveals that the proposed FSS has very high reflectivity at 2.45 GHz. Therefore the FSS structure is suitable for use with the antenna, designed in section 3. The final FSS structure (Fig. 13b) is a 9×15 element periodic array of the unit cells shown in Fig. 13a and has dimensions $65 \times 70 \text{ mm}^2$.

5. FSS LOADED ANTENNA

In the final stage of the antenna design, the developed FSS is placed below the ground plane of the antenna with the help of four Bakelite rods (Fig. 16). The distance between the FSS and the antenna was determined using a parametric analysis of the structure (Fig. 17). The optimized distance was found to be 15 mm (or $0.12 \lambda_0$).



Fig. 15 –Frequency response of the proposed FSS unit cell: a) magnitude of |S11| and |S21|; b) phase of |S11| and |S21|.

Comparison of the frequency response of the antenna, with and without FSS is shown in Fig. 18. It reveals that the loading of FSS has no effect on frequency response.

Comparison of the simulated and measured gains of the proposed antennas (with and without FSS layer) is shown in Fig. 19. The figure reveals that in the entire 10 dB return loss bandwidth, gain of the FSS loaded antenna remains almost constant around 7.4 dBi with a maximum of 7.6 dBi at 2.5 GHz and a minimum of 7.4 dBi at 2.3 GHz respectively. It also reveals the gain of the FSS loaded antenna is almost 2.4 times more to that of the antenna without the FSS layer.

Simulated and measured co- and cross polarization radiation patterns of the proposed FSS loaded antenna on both orthogonal planes at 2.45 GHz are shown in Fig. 20. The suppression of back lobe is observed, as expected. It also reveals that the cross polarization level is more than 18 dB down than the co-polarization level at the broadside direction on both the orthogonal planes. Radiation efficiency of the proposed antenna with FSS at 2.45 GHz is more than 82 % (Fig. 21).



Fig. 16 - Fabricated FSS loaded slant antenna.



Fig. 17 – Gain of the proposed FSS loaded slant antenna with the separation between the antenna and FSS layer.



Fig. 18 – Comparison of the simulated frequency response of the antenna, with and without layer.



Fig. 19 – Comparison of the simulated and measured gain response of the antenna, with and without FSS layer.



Fig. 20 – Normalized co- and cross-polarization radiation patterns of the proposed FSS loaded antenna at 2.45 GHz on a) *yz*-plane b) *xz*-plane.



Fig. 21 -Simulated radiation efficiency of the antenna.

6. CONCLUSION

This paper presents a high gain single band slant antenna for 2.45 GHz wireless power transfer application. Initially a rectangular slot DGS loaded slant antenna was proposed, which showed a number of other 10 dB return loss bands in addition to the required 2.45 GHz band. To remove these bands, two stubs have been used with the feed line and one U shaped DGS has been etched on the ground plane, beneath the feed line. The additional structures behave as bandstop filter and remove the unnecessary bands. The improved antenna showed a 3.1 dBi gain at the operating frequency. To improve the gain, next a 2.45 GHz reflector type FSS structure has been developed and placed below the ground plane. The FSS reflects the backscattered wave at 2.45 GHz which is then and added to the radiated field in the broadside direction in phase and result in gain enhancement. The FSS loaded antenna has 7.57 dBi gain, 82 % radiation efficiency, and single operating band at 2.45 GHz which makes it suitable for wireless power transmission.

It may be noted that even though a simple full ground plane in place of the FSS can serve the purpose of gain improvement at the desired frequency, it cannot be used in the present case because of its scattering properties at all frequencies. For a PEC ground plane, the scattering of the out of band signals will introduce unnecessary field coupling with the radiating elements and will introduce additional bands in the frequency response of the antenna. Further, the gain enhancement that can be achieved by a plane reflector at 2.45 GHz will be less than that provided by a well-designed FSS.

REFERENCES

- S. Ladan, N. Ghassemi, A. Ghitto, Ke Wu, *High efficient compact Rectenna for wireless energy harvesting application*, IEEE microw. magazine, 14, 1, pp. 117–122 (2013).
- A. Khemar, A. Kacha, H. Takhedmit, G. Abib, *Design and Experiments* of a 3G-Band Rectenna for Radio Frequency Energy Harvesting, Rev. Roum. Sci. Techn – Électrotechn. et Énerg., 62, 1, pp. 82–86 (2017).
- Y. Horii, M. Tsutsumi, *Harmonic control by photonic bandgap on microstrip* patch antenna, IEEE Microw. Guided Waves Lett., 9, 1 pp. 13–15 (1999).
- H. Liu, Z. Li, X. Sun, J. Mao, Harmonic suppression with photonic bandgap and defected ground structure for a microstrip patch antenna, IEEE Microw. Wireless Compon. Lett., 15, 2, pp. 55–56 (2005).
- Y.J. Sung and Y.-S. Kim, An improved design of microstrip patch antennas using photonic bandgap structure, IEEE Trans. Antennas Propag., 53, 5, pp. 1799–1804 (2005).
- M. Militaru, G. Lojewski, M. G. Banciu, *Microwave Compact Filters* Using Multilayer Structures, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., 53, 4, pp. 463–472 (2008)
- Y. Sung, M. Kim, Y. Kim, Harmonics reduction with defected ground structure for a microstrip patch antenna, IEEE Antennas Wireless Propag. Lett., 2, 1 pp. 111–113 (2003).
- M. G. Banciu, N. Militaru, *Effects of Ground-slots on the couplings of microstrip hairpin resonators*, Rev. Roum. Sci. Techn Électrotechn. et Énerg., 52, 1, pp. 61–66 (2007).
- S. Biswas, D. Guha, C. Kumar, Control of Higher Harmonics and Their Radiations in Microstrip Antennas Using Compact Defected Ground Structures, IEEE Trans on Antennas and Propag., 61, 6, pp. 3349– 3353 (2013).
- C-Y-D Sim, M-H Chang, Bo-Yu Chen, Microstrip-Fed Ring Slot Antenna Design with Wideband Harmonic Suppression, IEEE Trans on Antennas and Propag., 62, pp. 4828–4832, 2014.
- Z. Ma, Guy A.E. Vandenbosch, Wideband Harmonic Rejection Filtenna for Wireless Power Transfer, IEEE Transon Antenna and Propag., 62, 1, pp. 371–377 (2014).
- F-J Huang, T-C Yo, C-M Lee,C-H Luo, *Design of Circular Polarization Antenna with Harmonic Suppression for Rectenna Application*, IEEE Antennas and Wireless Propag. Lett., **11**, pp. 592–595 (2012).
- H. Kim, K.S. Hwang, K. Chang, Y.J. Yoon, Novel Slot Antenna for Harmonic Suppression, IEEE and Wireless Component Lett., 14, 6, pp. 286–288 (2004).
- H. Kim, Y.J. Yoon, H. Kim and Y.J. Yoon, *Microstrip-fed slot* antennas with suppressed harmonics, IEEE Trans. Antennas Propag., 53, 9, pp. 2809–2817 (2005).
- D-H Choi, Y-J Cho, S-O Park, A Broadband Slot Antenna with Harmonic Suppression, Microwave and Optical Technology Lett., 48, pp. 1984–1987 (2006).
- Y. Xu, Shuxi G., T. Hong, Circularly Polarized Slot Microstrip Antenna for Harmonic Suppression, IEEE Antennas and Wireless Propag. Lett., 12, pp. 472–475 (2013).
- B. Lindmark, M. Nilsson, On the available diversity gain from different dual-polarized antennas, IEEE Journal Selected Areas Communications, 19, 2, pp. 287–294 (2001).
- A. Dastranj, B. A-Arand, High-Performance 45^oSlant-Polarized Omnidirectional Antenna for 2–66-GHz UWB Applications, IEEE Trans Antennas Propag., 64, 2, pp. 815–820 (2016).
- K. Sarabandi, N. Behdad, A Frequency Selective Surface With Miniaturized Elements, IEEE Trans. on Antennas and Propa., 55, 5, pp. 1239–1245 (2007).