Modified Truncated Patch Antenna for S-Band Wireless Power Transmission Rectenna

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Abstract

A rectifying antenna or rectenna consists of an antenna and a low-pass filter, placed at the front-end of a wireless power transmission receiving system. This paper presents the design of a modified truncated square patch antenna having electromagnetic coupling feed operating at S-band of 2.45 GHz. The basis of the design is the conventional microstrip square patch antenna. The antenna was truncated for circular-polarization capability. Further modification in the form of embedded slits at the four corners was done and the performance was investigated. It was found that the configuration operates well at the desired frequency of operation.

1. INTRODUCTION

The conceptual of transmitting power without the use of wire or any physical medium has been introduced by Nikola Tesla almost a century ago [1]. Researchers all over the world hardly study the potential of Wireless Power Transmission (WPT) to realize the idea of collecting sun energy through solar panels located in the space or known as Solar Power Satellite. In the development of Solar Power Satellite, a few stages are involved in order to collect the sun energy from space and then transmit it to the earth grounds. Rectenna system is one of the stages in receiving the power where it is located at the reception side [2]. One such method of delivering power from one point to another through wireless is using the microwave frequency. A WPT system consists of the source of energy which is beamed through microwave frequency to its corresponding receiving system. The WPT reception front-end is made up of a rectenna or rectifying antenna which is used to receive the transmitted power through space and converting the power to electricity. The converted electricity can be used for energy storage.

At Universiti Teknologi Malaysia, the research studies the development of the microwave power source [3], receiving antenna [4]-[7] and low pass filter candidates [6]-[8]. The rectenna circuit is made up of a receiving antenna, low pass filter and rectifying circuits as shown in Figure 1. The front-end of a rectenna is an antenna and LPF. The LPF located between the antenna and the rectifying circuit needs to be designed so that the fundamental frequency can be passed whilst a portion of the higher order harmonics generated from the rectifying circuit is rejected back to the rectifying circuit [2].

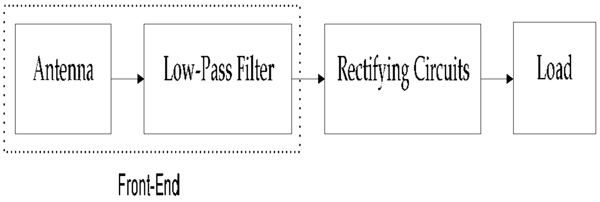

Fig. 1: Block diagram of a rectenna circuit and load.

This paper presents the design of a rectenna candidate, based on the truncated square patch. Several work on the rectenna candidate showed continued interest globally [9]-[12].

2. DESIGN OF MODIFIED TRUNCATED SQUARE PATCH ANTENNA

Firstly, an appropriate substrate is chosen since the choice can affect the antenna performance [13]-[14]. A low dielectric constant can reduce the dielectric loss and surface wave excitation. A sufficiently thick substrate can maximize bandwidth and efficiency, without risking surface wave excitation. Sufficiently low loss tangent allows efficient antenna to be obtain while it lowers feed losses.

To design a square patch, the lowest resonant frequency, f_r, is first specified. The width, W is chosen as equal to its length, L [13]-[14]. A $W = L$ size has the advantages of avoiding higher order modes that may disturb the radiation pattern and to obtain a high radiation efficiency. Hence, initial value of dimensions W and L for a particular substrate of relative permittivity ε_r can be computed using the formulation:

$$W' = L' = \frac{c'}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (1)$$

where $c' = 3 \times 10^8$ m/s being the speed of light.

The line extension, ΔL, due to the fringing fields is given by:

$$\Delta L = 0.412h \frac{(\varepsilon_{re} + 0.3)\left(\frac{L'}{h} + 0.264\right)}{(\varepsilon_{re} - 0.258)\left(\frac{L'}{h} + 0.8\right)} \quad (2)$$

where the effective relative permittivity for the substrate of thickness h is given by:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{L'}\right]^{-0.5} \quad \text{for } L'/h \geq 1 \quad (3)$$

Hence, the effective length is computed with

$$L = \frac{c'}{2 f_r \sqrt{\varepsilon_{re}}} - 2\Delta L \quad (4)$$

and equals the final width of the antenna, W.

The basic square patch antenna exhibits a linear polarization [13]-[14]. It can be described from the radiation mechanism of the patch. Fringing fields exist at the edges of the patch length. The fields at the end are composed of normal and tangential components with respect to the ground plane. The normal components are perpendicular to the ground plane and separated by $\lambda/2$. The total components are 180^o out of phase and equal in magnitude. Therefore, their radiations cancel in the broadside direction. The tangential components are parallel to the ground plane. In the plan view, the components are equal in magnitude and phase. This leads to a broadside radiation pattern in the $+z$ direction. The patch radiation is hence linearly polarized in the x-z plane, where the wave propagates in the $+z$ direction.

The basic square patch was fed with electromagnetic coupling, to avoid direct soldering to the radiating patch, and hence avoid any radiation power loss. The feed point was determined as that of a probe-fed. The antenna is truncated at two opposite edges, for producing the desired right-hand circular polarization (RHCP), as shown in Figure 2.

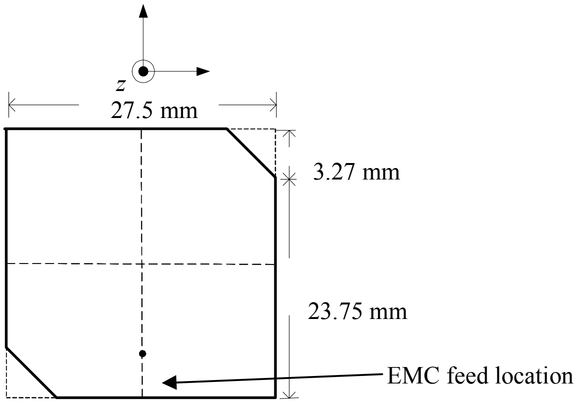

Fig. 2: Geometry of CTSP_E3 and EMC feed location.

The location of the feed on the patch can be determined using formulations available in the literature [13]-[14]. Further modification is done by adding slits, firstly at the truncated corners. Then the slits were added at all corners.

3. Numerical Investigations

Figure 3 shows the simulated return loss and RHCP and LHCP patterns of the CTSP_E3 in the y-z plane using electromagnetic simulation software [15]. Dual resonances at f_{r1} = 2.444 GHz and f_{r2} = 2.51 GHz were observed. These are due to the perturbations introduced. The antenna does not exhibit a good circular polarization since the pattern peak of AR is above 3 dB. This could be due to the length of c that does not proportionate to the excitation of orthogonal modes of the circular polarization [16]. Hence, its size was decreased until a good circular polarization is achieved. It is observed that c = 1.875 mm produces the best AR response with 3-dB AR bandwidth of 7.5 MHz or 0.31%. At 2.453 GHz, the minimum AR is 1.6 dB while at 2.45 GHz, it is 2.39 dB. However, the AR of 2.45 GHz is still within the range of circularly polarized bandwidth since the bandwidth of circular polarization is determined from the AR with pattern peak of 3 dB or less. AR responses are in Figure 4. The antenna is very well matched at 2.464 GHz with -14.77 dB return loss.

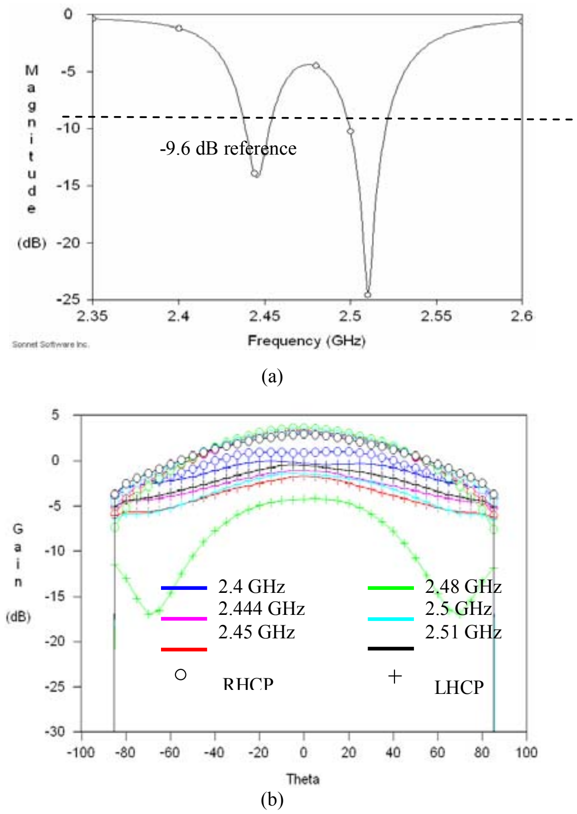

Fig. 3: Simulated responses of CTSP_E3 with L = 27.5 mm and c = 3.27 mm (a) return loss (b) RHCP and LHCP patterns at y-z plane.

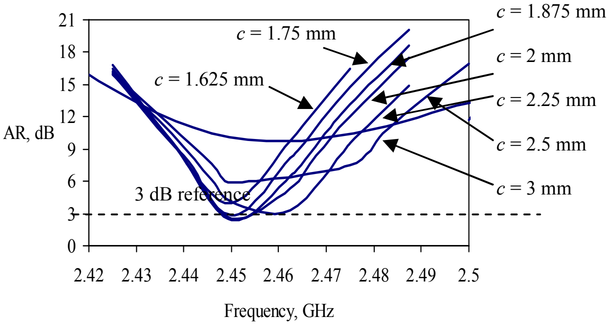

Fig. 4: AR with decreasing c of CTSP_E3 with L = 27.5 mm. Best response is achieved when c = 1.875 mm.

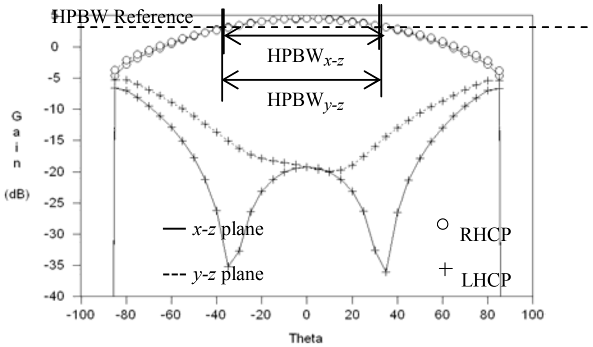

Fig. 6: Simulated radiation patterns in the x-z and y-z plane of CTSP_E3 with L = 27.625 mm and c = 2 mm

However, the dimensions of the CTSP_E3 are then modified for the desired 2.45 GHz operation. It was found to be optimum with L = 27.625 mm, c = 2 mm, and very good return loss of -23.41 dB at 2.45 GHz as shown in Figure 5. The AR at is 2.2 dB while the minimum AR is 1.13 dB at 2.453 GHz. The frequency of 2.453 GHz is defined as f_{cCP}, the centre frequency of circular polarization where its AR is minimum. These responses are better than that of L = 27.5 mm with c = 1.875 mm. The CP bandwidth is slightly better, i.e. 9 MHz or 0.37%. Figure 6 shows the circular polarization radiation pattern in the x-z and y-z planes at 2.453 GHz. It is observed that the sense of circular polarization is RHCP, which agrees well with theory. The gain is 4.5 dBi which is slightly lower than that of SP_E3 as expected due to slightly lower maximum current density along the patch edges. The HPBWs are 105^o and 110^o for the x-z and y-z plane, respectively.

The antenna is then modified by inserting slots into the corners forming SCTSP antenna as illustrated in Figure 7(a). Before any slit insertion, the simulated current distribution shows high densities at the centre of every edge length while low at the corners of the patch. If slits with equal length, l_{sl} and width, w_{sl} are inserted at each corner of the patch, the current along the lengths is expected to be undisturbed hence this maintains the performance of the antenna. These inserted slits will electrically lengthen the antenna and effectively lowers the resonant frequency of the modified CTSP.

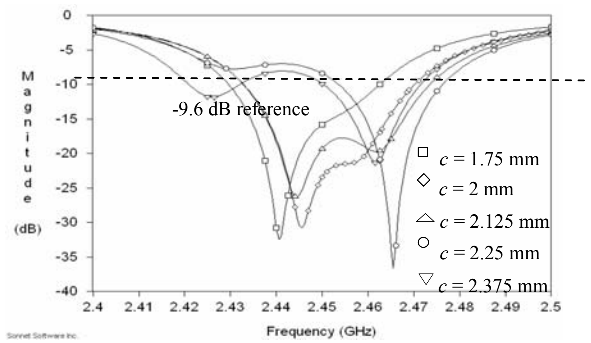

Fig. 5: Simulated return loss responses of CTSP_E3 with L = 27.625 mm and increasing c.

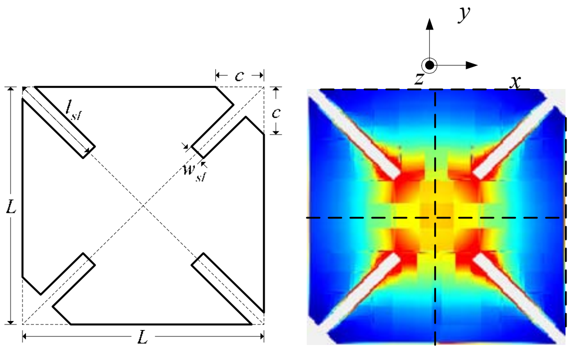

Fig. 7: SCTSP antenna (a) geometry (b) current distribution.

With the insertion of the slits, it is expected to lower the resonant of the antenna, thus, a compact structure can be achieved. The length of SCTSP was chosen to be 23 mm which will resonate slightly higher than 2.45 GHz. The inserted slit at each corner will decrease the fundamental resonant frequency back to the desired value. The simulated current distribution appears meandered and gathered at the end of each slit near the centre of the patch. This effectively decreases the fundamental resonant frequency. The orthogonal current distributions along the patch edges exhibit the same pattern as that of CTSP_E3 which are of half-wave sinus shape. But the current distributions are high at the centre of the patch. This is probably due to the insertion slits at the corners of the CTSP where some portion of the current meandered and accumulated at the end of each slit near the centre of the patch. However, the maximum current density along the patch edges is 15.2 Amps/m, which is lower than that of CTSP_E3. The decreased maximum current density degrades the antenna gain.

Figures 8 and 9 show the simulated return loss with L = 23 mm and radiation pattern, respectively. The antenna resonates at 2.913 GHz with good return loss of -27.83 dB and narrow VSWR bandwidth of 25 MHz or 0.86%. The simulated gain is 4.92 dBi, HPBWs are 160^o and 84^o for the E- and H-plane, respectively, and maximum current density along the patch edges is 34.3 Amps/m. The simulated gain agrees with theory and HPBWs are in the range of a typical square patch microstrip antenna's HPBW [17].

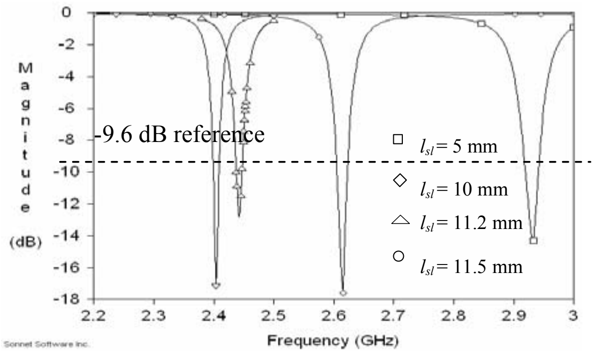

Fig. 8: Simulated return loss response of SCTSP_E3 with L = 23 mm and c = 1.625 mm for various l_{sl} sizes.

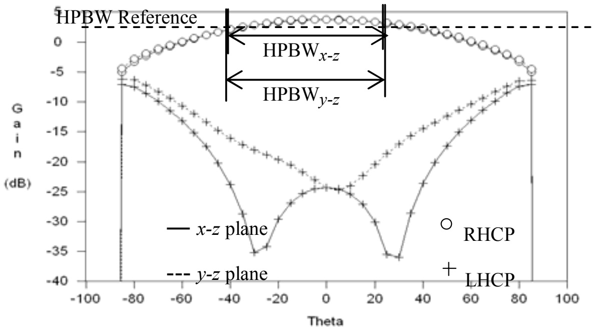

Fig. 9: Simulated radiation patterns in the x-z and y-z plane of SCTSP_E3 with L = 23 mm, l_{sl} = 11.2 mm and c = 2.5 mm.

4. Conclusion

A modified truncated square patch antenna having electromagnetic coupling feed operating at S-band of 2.45 GHz has been presented. The basis of the design is the conventional microstrip square patch antenna. The antenna was truncated for circular-polarization capability. Further modification in the form of embedded slits at the four corners was done and the performance was investigated. It was found that the configuration operates well at the desired frequency of operation.

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References

[1] N. Tesla, "The transmission of electric energy without wires", *The 13th Anniversary Number of the Electrical World and Engineer,* 1904.

[2] Hiroshi Matsumoto, "Research on Solar Power Satellite and Microwave Power Transmission in Japan", *IEE Microwave Magazine*, vol. 3, 2004.

[3] Kamarul Hawari Ghazali and Mazlina Esa, "High Power Amplifier Prototype for Wireless Power Transmission Reception", *Proc of 2004 Malaysia Science and Technology Congress* (MSTC2004), Palace of the Golden Horses, Sg Besi, Malaysia, 5-7 October 2004.

[4] Mazlina Esa, Ikhwan Peranggi Pohan, Jasmy Mohd Yunos, Noor Asniza Murad and Kamarul Hawari Ghazali, "S-Band Antenna Candidate for The Front-End Rectenna of the WPT Prototype Reception", *Proc of 2004 Malaysia Science and Technology Congress* (MSTC2004), Palace of the Golden Horses, Sg Besi, Malaysia, 5-7 October 2004.

[5] Mazlina Esa, Noor Asniza Murad, Ikhwan Peranggi Pohan, Rosmawati Othman and Adnall Bakar, "Modified Bifin Fractal Antenna with Size Reduction", *Proc of 2004 Radio Frequency and Microwaves* (RFM2004), Hyatt Regency Saujana, Subang, Malaysia, 4-6 Oct 2004.

[6] Mazlina Esa, Ikhwan Peranggi Pohan, Noor Asniza Murad and Jasmy Yunus, "Front-End Rectenna Components – Slitted Antenna and Elliptic Filter", *Proc of 2005 Malaysia Science and Technology Congress* (MSTC2005), Cititel Midvalley, Kuala Lumpur, Malaysia, 18-20 April 2005.

[7] Ikhwan Peranggi Pohan, *A Compact S-Band Front-End Rectenna for Wireless Power Transfer Application*, unpublished dissertation, Universiti Teknologi Malaysia, Malaysia, February 2006.

[8] Ikhwan Peranggi Pohan, Mazlina Esa, Jasmy Mohd Yunus and Noor Asniza Murad, "Filter Candidate for the Front-End Rectenna Prototype of a WPT Reception", *Proc. of Intl. Electronics Seminar*, Indonesia, Nov. 2005.

[9] Suh, Y. H., Wang, C., and Chang, K., "Circularly polarized truncated-corner square patch microstrip rectenna for wireless power transmission", *Electronics Letters*, vol. 36, no.7, pp.600-602, 2000.

[10] McSpadden, J. O. and Chang, K., "A dual polarized circular patch rectifying antenna at 2.45 GHz for microwave power conversion and detection", *IEEE MTT-S Int. Microwave Symp. Dig*, 3, pp.1749-1752, 1998.

[11] Fujino, Y., Kaya, N., and Saka, T., "Development of C-band rectenna for microwave power transmission toward a space robot", *Acta Astonautica*, vol. 50, pp.295-300, 2002.

[12] Yoo, T., McSpadden, J. O. and Chang, K., "35 GHz rectenna implemented with a patch and a microstrip dipole antenna", *IEEE MTT-S Digest*, vol. 1, pp.345-347, 1992.

[13] C. A. Balanis, *Antenna Theory and Design*, Wiley, 3rd edn, 2005.

[14] David M. Pozar, *Microwave Engineering*, 3rd Ed, Wiley, New York, 2005.

[15] http://www.sonnetusa.com

[16] D. Wu and J. Huang, "CAD and optimization of circularly-polarized microstrip arrays", *IEEE Antennas Propagat. Society Int'l Symp.*, Vol. 3, pp1840-43, 1994.

[17] D. M. Pozar, and D. H. Schaubert, "*The Analysis and Design of Microstrip Antennas and Arrays*", A Selected Reprint Volume. IEEE Antennas and Propagation Society Sponsor. New York, 1995.