Harmonics Suppression Single-fed Dual-Circularly Polarized Microstrip Patch Antenna for Future Wireless Power Transmission

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***Abstract*—This paper presents a novel design of a harmonic suppression single-fed dual-circularly polarized microstrip patch antenna for a rectenna system in the future wireless power transmission application. The proposed antenna is capable of receiving both types of circular polarization signal; RHCP and LHCP simultaneously and at the same time it also able to filter the unwanted harmonic signals itself. These characteristics are achieved after introducing a circular slot defected ground structure to an array of nearly-square microstrip patch antenna with an offset inset microstrip feeding line and two open stubs on the feeding line. The proposed antenna is very simple on the single substrate only and this led to a reduction of errors that occurs during the fabrication process. However, the most importantly is the possibility of the polarization mismatch during transmission of signal can be minimized and the use of additional harmonic filter circuit can be eliminated. Thus the rectenna system becomes smaller, cheaper, less complexity and more efficient. The overall structure of the proposed antenna is designed on the top surface of the PCB only, thus it can be interfaced with other circuit such as rectifier or other circuit easily. The Computer Simulation Technology (CST) has been used in the simulation and optimization of the design. Finally, for the verification of the design, the prototype of the proposed antenna is fabricated and measured. From the simulation and measurement results, the proposed antenna can be a good choice in the rectenna system for future wireless power transmission application.**

Keyword - Harmonic suppression, microstrip patch antenna, circularly polarized, dual-circularly, wireless power transmission, rectenna system

I. INTRODUCTION

In the past few years, there was a lot of effort in exploring a new sources of energy to generate electricity as an alternative to the existing technology which mostly depends on the fuel energy. One of the most promising candidate is the solar energy. The solar energy is a renewable, clean and green energy has gained attention as it is consistent than the other sources such as wind energy, ocean wave energy or thermal energy. Therefore, there are many solar panels have been built to harvest sunlight energy and convert it to an electricity such as in remote villages in the forest or island and on the top of buildings. Other than clean and green, the advantage of this energy is the consumer is required to invest at the beginning of the installation only, then they can enjoy it for free. However, there are also problems arise in the use of the solar energy as the sunlight source is not consistent due to change day and night, weather and season. Recently, there is an effort to build a solar panel facing the sun directly in the outer space to harvest the solar energy at all the time which is named as space solar power station (SSPS) [1-2]. Then the harvested energy is transported to the earth power station for the humankind used. However, a main problem to be solved to realize this ambition is the process to bring the harvested energy from the space station to the earth station. The only way to transport this energy is the through a transmission of the power without wire. But the wireless power transmission technology (WPT) used to bring this energy to the earth has not been developed yet. In order to implement the wireless power transmission (WPT) technology in the SPSS system successfully, a high efficiency system is required. These are the main challenges in the development of wireless power transmission systems. Most of the researchers in the literature focusing on the receiving part of WPT system which is named as a rectenna system [3-10]. The rectenna system is an integration of the rectifying circuit and the receiving antenna. The wireless transmitted energy which is in RF waveform signal is collected by the receiving antenna. Then that RF signal is converted to a DC signal by the rectifier circuit.

The efficiency of the overall WPT system depends on how much the amount produced by the rectenna system which is dependent on how much the RF energy is collected and then converted to the DC signal. In order to optimised the efficiency of the rectenna system, the losses of energy during receiving and conversion of signal processes should be minimised. The factors that affect the amount of energy can be collected by the receiving antenna is the interference of the transmitting signal in the free space such as EMI interference and noises from the other sources of RF system. There is also an internal noise in the rectenna system itself, known as unwanted harmonic signals which is generated by the diode in the rectifier circuit. A diode is a nonlinear device, function as a switch used to rectify the RF signal to DC signal in the rectifier circuit. The switching characteristic of diode which allows only one cycle of the RF current flow through it causes the other cycle of RF current is bounced back to the source (i.e. receiving antenna) at the harmonic frequencies. This signal is then combined with the collected signal and produce a disturbed signal. This weak signal then flows to the rectifier circuit for the RF-to-DC conversion; the process is repeated as before. As the result the output of the rectenna is low. In normal RF front end communication, a filter is used to attenuate all these noises, EMI interference and the harmonic signals. To implement the filter circuit in any system, the connection of the filter circuit with other circuit such as antenna must be perfectly matched, otherwise a maximum of power cannot be transferred between them. If they are not matched, a matching circuit must be introduced in between these circuits. However, this technique cannot be implemented in the rectenna system because the implementation of this technique will introduce an additional losses contribute by this additional circuit; filter and matching circuit, known as an insertion loss which affected the system efficiency. One of the technique to attenuate these unwanted harmonic signals in the rectenna system is the implementation of harmonic suppression antenna which is widely used in wireless power transmission [4-12]. It also has been used as a load harmonic tuner in high efficiency class-F power amplifier [13-14] and active integrated antenna system [15-16]. This special antenna can work as a radiating element and at the same time able to filter the harmonic signals. To achieve these characteristics, the antenna must have a good impedance matching at the fundamental frequency while unmatched at the harmonic frequencies. There are a lot of technique and design of a harmonic suppression antenna presented in the literature, such as the implementation of the slit and the stub in microstrip patch antenna structure [7-8], a circular sector patch antenna [13], a photonic band gap structure [17-19], a defected ground structure (DGS) [8,12], and SIR ground [20].

Another loss occurred in the WPT system is the polarization of wave loss due to the mismatch of the wave polarization between the transmitting and receiving antenna. In order to minimize the polarization losses, both polarizations of the transmitting and receiving antenna must be well matched. A circularly polarized antenna can be used to avoid the polarization mismatch because the position of this antenna type is more flexible. It is able to maintain a constant output even though the transmitter or the receiver misalignment due to its ability to radiate or receive waves in circulation and always perpendicular to the direction of the propagation [21-24]. The circular polarization wave is divided into two types of polarization, which depend on its rotation; the left hand circular polarized (LHCP) and the right hand circular polarized (RHCP). These polarizations depend on the polarization of the antenna. To receive the transmitted signal effectively, the polarization of the receiving antenna must be matched with the polarization of the wave, which is the same as the polarization of the transmitting antenna. Usually, the waves will be refracted or reflected if there are obstacles on the way of the signal transmission journey. As a result, the polarization of the wave will be changed and the problem will only arise if the polarization of the receiving antenna is different. However, to solve this problem, the receiving antenna which capable of receiving both types of polarization should be used. In the literature, some kinds of antenna with dual circularly polarized characteristics has been proposed. In [25], a dual circularly polarized patch antenna fed by an L-strip has been proposed. In order to generate two circular polarization, the dual input ports technique has been used. The diversity of the polarization between the LHCP and RHCP is provided by switching the two ports. A reconfigurable microstrip patch antenna with a polarization switching technique is proposed in [26]. A single polar double throw (SPDT) switch is used to switch between the LHCP and RHCP polarization types. It also consists of a 3 dB hybrid coupler and needs a DC bias network. A multilayer antenna to provide dual circularly polarized characteristics has also been proposed. A three layer structure antenna with a dual input port, which was proposed by [27], while [28] proposed a three layer with 4 input ports. A dual circularly polarized patch antenna with two patches and one input is proposed in [29].

As a summary of a lot of design techniques in the literature, most of the designs use the probe feed, proximity feed and aperture couple feeding technique. They are also used multilayer substrate to suppress the harmonic signal and dual feed to provide dual circular polarization wave. These techniques are quite difficult and complex. They require high precision design and manufacture, and result in increased costs, size and weight. In addition, some of the designs also use a coaxial probe feed as a feeding technique, which needs high precision drilling and soldering of the probe feed. A longer probe is needed for a thick substrate of the antenna, thus the inductance due to the feed and surface power will increase. Moreover, to develop the patch antenna in array form, a large number of probe feed solder joints are needed to form an array structure, which can lead to an increase in the losses. Some of the proposed antennae have a very complex slot structure, which require precision design and fabrication. Any small error in fabrication will cause it to not function as intended.

In this paper, a harmonic suppression single-fed dual-circularly polarized microstrip patch antenna for the rectenna system in wireless power transmission is proposed. The structure of the proposed design is very simple patch shape with only single microstrip feeding line on a single substrate. The proposed design also has the capability of easy integration with the other planar circuits or systems and can be easily extended to form an array. The details of the design of the proposed antenna are described in the following chapter.

II. ANTENNA DESIGN

From a basic rectangular shape patch antenna, a nearly-square circularly polarized microstrip patch antenna is developed by a segment perturbation of the basic rectangular patch structure with an offset microstrip feeding line technique. To improve the input impedance matching, a quarter-wave impedance transformer section in the transmission line feed is applied. The proposed antenna is then plotted and simulated using the commercial Computer Simulation Technology (CST) Microwave Studio simulator. The structure of the basic circularly polarized nearly-square microstrip patch antenna is shown in Figure 1(a). The analysis using cavity and equivalent circuit model of this nearly-square microstrip patch antenna is derived and presented in [30-32]. As mentioned before, the beauty of the microstrip line feeding technique is very easy to be extended in array form. Then four elements of a nearly-square patch, which were developed previously, are connected together with a simple microstrip transmission line to produce a two by two array structure. To suppress the harmonic signals, the offset feeding line structure is then replaced by the offset inset feeding line. The defected ground structure (DGS) technique with a circular slot on the ground plane of each patch is introduced. Also, two open stub structures are introduced on the feeding line. The geometry of the proposed structure is shown in Figure 1(b) and (c).

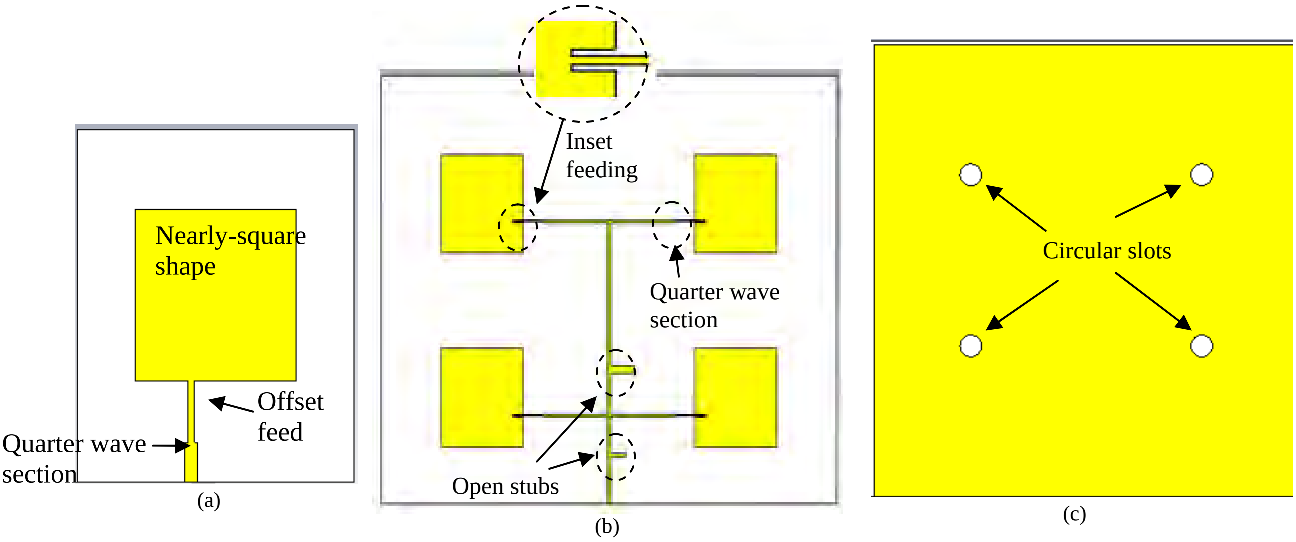
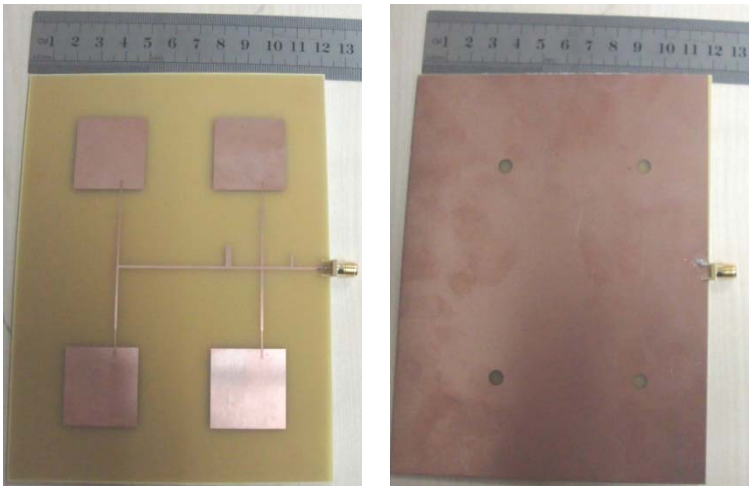


Figure 1: (a) A geometry of CP nearly-square patch antenna, (b) front view of the proposed antenna and (c) ground plane view

These structures are proposed to control the flow of current to each the patch. As the result, the input impedance of the antenna is well matched at the fundamental frequency while unmatched at the harmonic frequencies. This causes the transferred of power to the patches is only maximum during the fundamental frequency. Thus the patch antenna resonates effectively at the fundamental frequency and unable to resonate at harmonic frequencies due to the power that can be transferred to the patch at that particular frequency is very low. With this situation, this antenna is working as a radiator at the fundamental frequency and working as a filter at the harmonic frequencies. The detailed analysis of the proposed harmonic suppression single-fed dual-circularly polarized antenna is discussed in the following section.

For the verification of the design, the prototype of the proposed antenna design is then fabricated using a standard printed circuit board (PCB) process with FR4 substrate, dielectric permittivity of 4.7 and a thickness of 1.6 mm, and copper thickness of 35 μm. The image of the fabricated prototype is shown in Figure 2.



(a) Front view (b) Ground plane view

Figure 2: The fabricated prototype of harmonic suppression single-fed dual-circularly polarized microstrip patch antenna

III. ANTENNA MEASUREMENT

To validate the proposed design, the experimental work to measure the performance of the antenna is carried out. The reflection coefficient and the input impedance of the prototype is measured with the PNA Network Analyzer (Agilent, E83262B). Then the radiation pattern of the antenna is measured in the anechoic chamber and the measurement setup is shown in Figure 3.

(a) Outside view (b) Inside view

Figure 3: Radiation pattern measurement in anechoic chamber

IV. RESULT AND DISCUSSION

In this section, the performance result of the proposed antenna is discussed. As mention previously, an antenna can be categorized as a harmonic suppression antenna if it is able to resonate at the fundamental frequency while attenuate at the harmonic frequencies. In this paper, a simple structure is proposed to a nearly-square patch antenna to produce an antenna that is able to resonate at the fundamental frequency and attenuate at the harmonic frequencies to use in a rectenna system for the future wireless power transmission. The proposed structures which are shown in Figure 1 (b) and (c) are able to control the amount of power to be transferred to the patch. As the result, the maximum of power is able to be transferred to the patch at the fundamental frequency only, while very low at harmonic frequencies. This condition is achieved because an input impedance is matched in the fundamental frequency only while unmatched at the harmonic frequencies. It is shown in the Smith chart in Figure 4. At the fundamental frequency, 2.45 GHz, 57 Ω of the input impedance is achieved. This impedance is perfectly matched to the system impedance. Thus the maximum of power can be transferred at that frequency. However, for the second and third harmonic frequency, the input impedances of the antenna are unmatched which causes very low of power can be transferred to the patch, thus it cannot be radiated at that particular frequency. The flow of current to the patch antenna is illustrated in Figure 5. It is shown that the concentration of current to the patch is high during 2.45 GHz only, while low in the second and third harmonic frequencies due to their impedance matching. The high concentration causes the patch resonates effectively at the fundamental frequency and at the second and third harmonic frequency, the patch cannot radiates due to low current. The proposed antenna is able to radiate in dual circular polarization, as shown in Figure 5 (a). There are two pairs of dual circular polarization patches – top and bottom. The right patches generate right hand polarization (RHCP) while the left patches generate left hand polarization (LHCP).

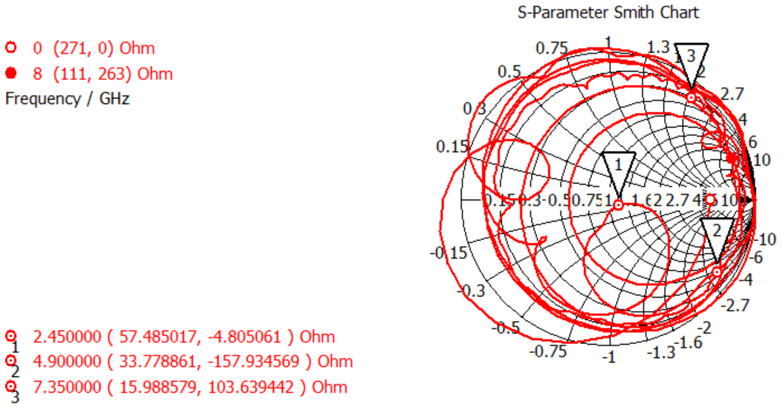
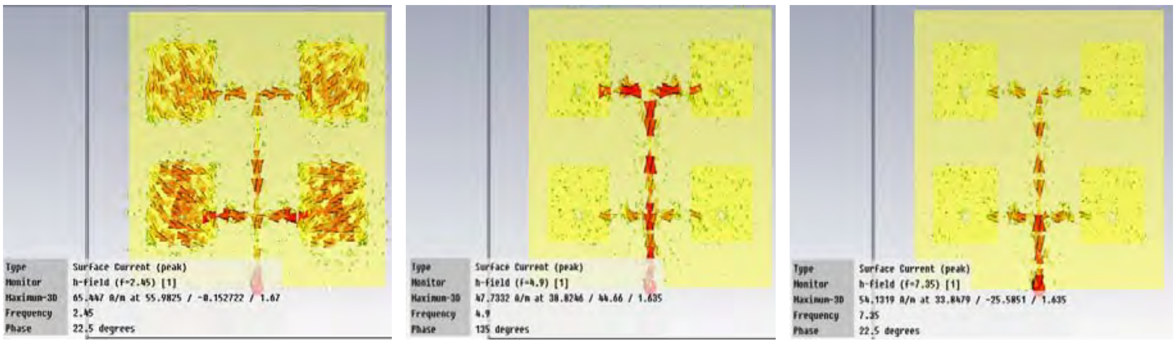


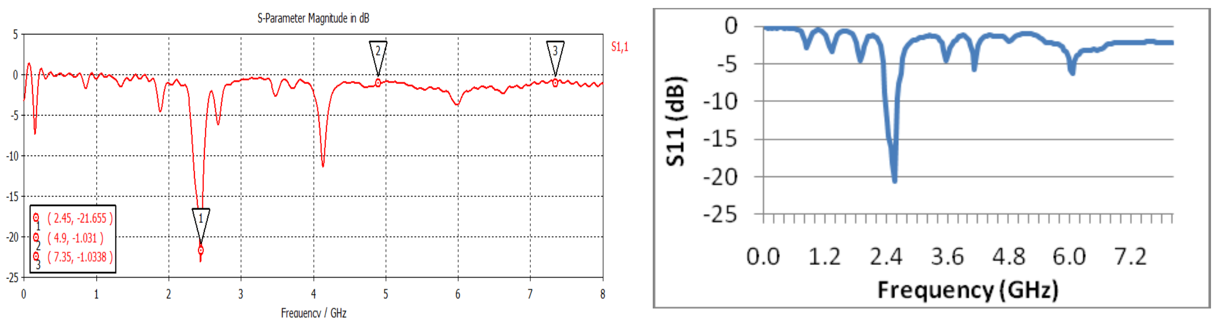
Figure 4: The Smith chart input impedances of the proposed antenna



(a) 2.45 GHz (b) 4.9 GHz (c) 7.35 GHz

Figure 5: The surface current plot of the proposed antenna

The S-parameter result of the proposed antenna is shown in Figure 6 (a). It represents the ability of the proposed antenna to radiate or reflects the input power. It is shown that, a -21.6 dB of the return loss is achieved at the fundamental frequency. It represented that, around 99% of the input power is able to be radiated by the proposed antenna. For both of the harmonic frequencies, the return loss of the antenna is successfully suppressed up to -1 dB. The simulation result of return loss of the proposed design is then be verified with the measurement of fabricated prototype as shown in the measured result in Figure 6 (b). The measurement shows that a -20 dB of the return loss is obtained at 2.45 GHz while for the second and third harmonic frequencies, the return loss is -1.1 dB and -2.1 dB respectively which means that the antenna is able to resonate at the fundamental frequency and the both of the harmonics are suppressed successfully.



(a) Simulation (b) Measurement

Figure 6: The return loss of proposed antenna

The axial ratio of the proposed antenna is shown in Figure 7 and shows that at 2.45 GHz frequency, the axial ratio is 0.26 dB, which is less than 3 dB and can be considered as a circular polarization wave is achieved.

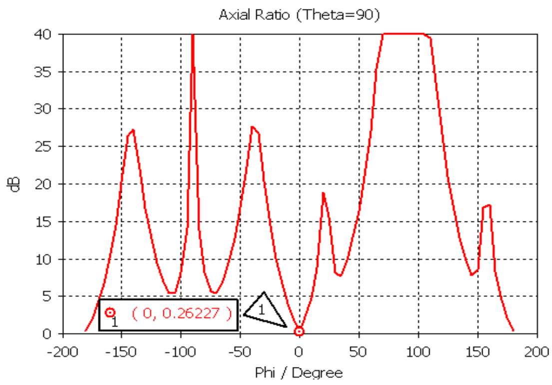


Figure 7: Axial ratio

The simulated 3D farfield radiation pattern of the antenna is shown in Figure 8. In Figure 8 (a), the total directivity of 9.887 dBi is obtained. The total gain of the antenna is 6.655 dB, as shown in Figure 8 (b), where the gain for the right polarization is 4.119 dB and 4.149 dB is for the left polarization as shown in figures 8 (c) and (d) respectively. This means that the proposed dual circular polarization microstrip patch antenna is able to radiate in RHCP and LHCP.

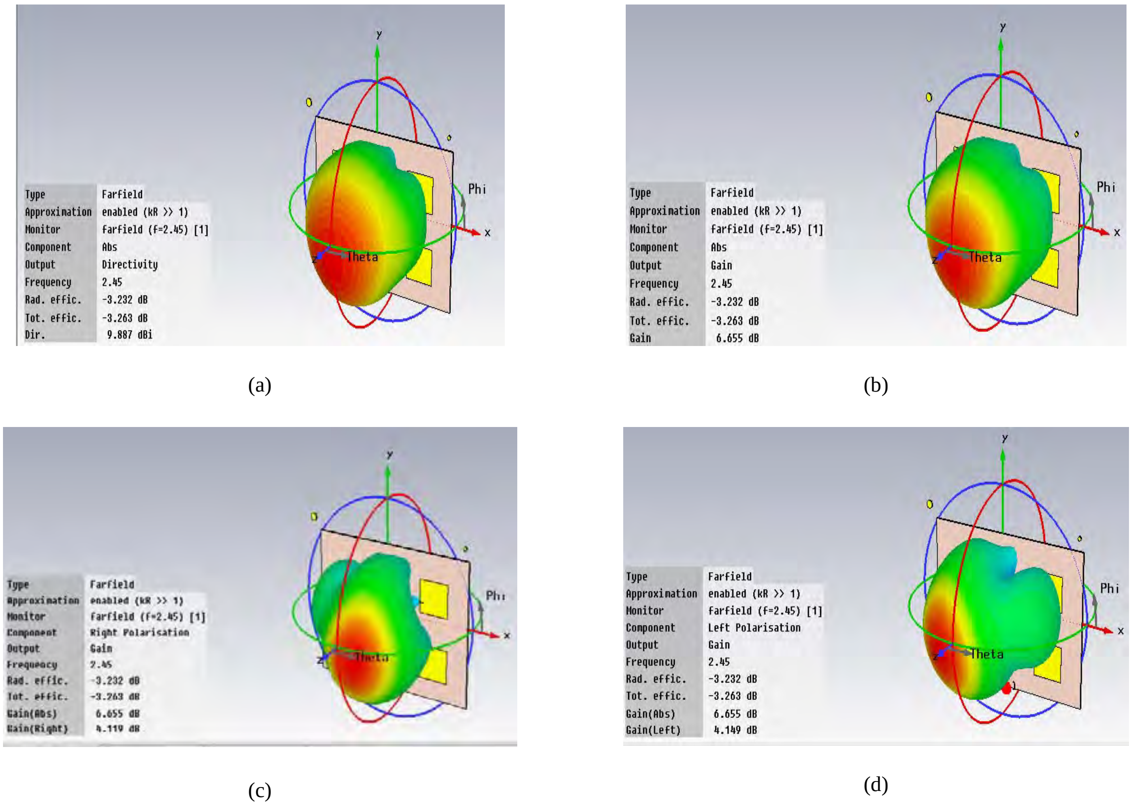
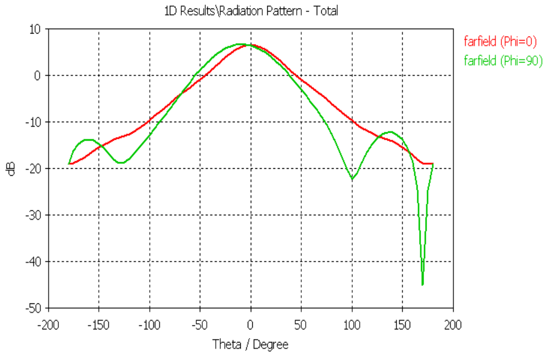
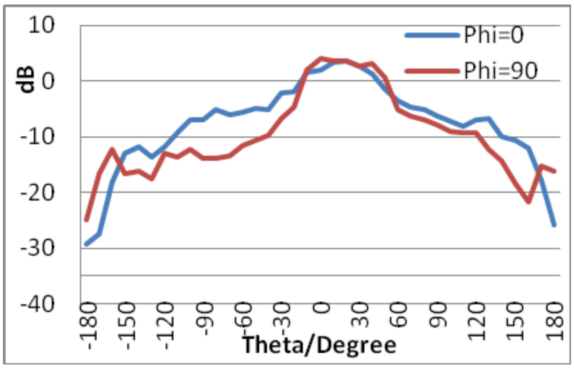


Figure 8: The simulated 3D Farfield radiation pattern of the proposed antenna

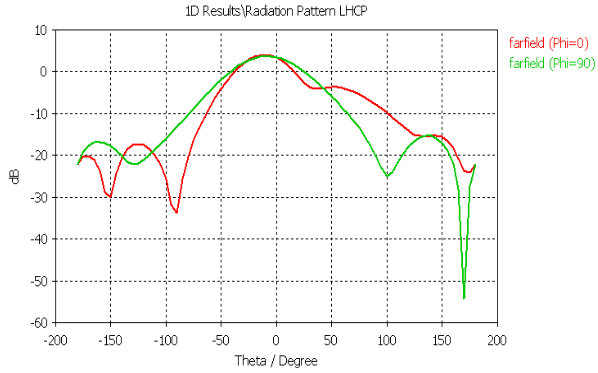
Figure 9 shows the 1D radiation pattern of the proposed dual polarization circularly polarized microstrip patch antenna. The E-field radiation pattern of the antenna is represented by Phi=0 graph and H-field is by Phi=90 graph. On the left hand side of Figure 9, shown the simulation result while on the right hand side shows the measurement result of the fabricated prototype of the proposed self-harmonic suppression dual polarization circularly polarized microstrip patch antenna design. It is shown that all the curves of the measured results are nearly the same pattern with the simulation results.



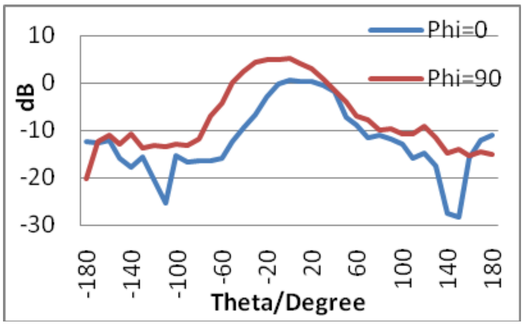
(a) Simulation – total



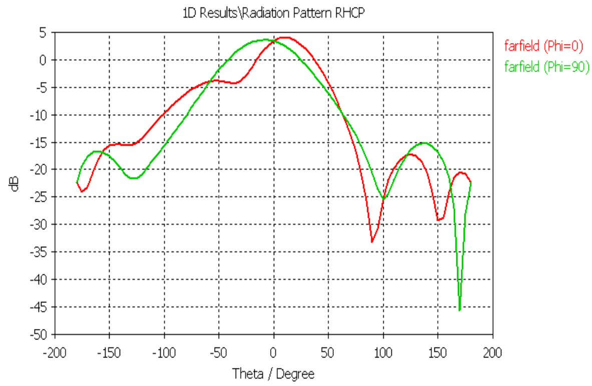
(b) Measurement - total



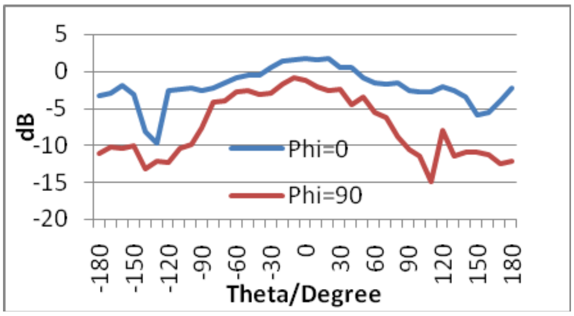
(c) Simulation – LHCP



(d) Measurement - LHCP



(e) Simulation –RHCP



(f) Measurement - RHCP

Figure 9: The 1D radiation pattern of the proposed patch antenna

V. Conclusion

In this work, the combination of an offset inset feeding line of the two by two nearly-square patches with a circular slot DGS and two open stubs at the feeding line are used to suppress magnitude of the return loss at the harmonic frequencies while resonates at the fundamental frequency successfully. The proposed antenna able to received dual circular polarization of waves which can minimise the polarization mismatch loss during the transmission of signal. The antenna is specifically proposed for rectenna system in future wireless power transmission system. This harmonic suppression antenna also can be used in any application which is need harmonic filter to attenuate the unwanted harmonic signals. The measurement of the fabricated prototype of the antenna is also conducted.

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