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Microstrip Array Antenna for Wireless Power Transfer

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Microstrip Array Antenna for Wireless Power Transfer

By

Sahereh Sahandabadi

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2021

Microstrip Array Antenna for Wireless Power Transfer

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ABSTRACT

In this thesis, a triangular microstrip patch antenna is used to transfer wireless power at 2.4 GHz. First, the simple patch antenna is studied and its performance is investigated. Then, the new design is introduced to boost the efficiency and transmission coefficient of the simple patch antenna. Since the simple patch aimed to operate at 2.4GHz, its dimension is optimized to be 56mm with a reflection coefficient of −28.2 dB at the resonance frequency. An identical patch acting as a receiver is then placed in a 50mm distance to the main patch acting as a transmitter to enable us to measure the power transferred to the receiver antenna. The transmission coefficient between the two simple patches is −3.5 dB at the resonance frequency of 2.4 GHz. Furthermore, the proposed array is designed and simulated yielding a reflection coefficient of −28 dB at 2.4 GHz. The same procedure for the simple patch is followed to obtain the transmission coefficient of −0.55 dB at 2.4 GHz. The simulation results show 89% efficiency for the proposed structure compared to the 44% efficiency of the single patch. Similarly, the structure is studied for 5.8 GHz and the corresponding results are provided. A titled version of the structure is also investigated and a similar efficiency as the original proposed structure is reported.

DEDICATION

To my family and friends. Without them, this wouldn’t have been possible.

To the soul of University of Windsor students who lost their lives on flight PS752.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS/SYMBOLS

Wireless Power Transfer	WPT
Wireless Energy Transmission	WET
Inductive power transfer	IPT
Electromagnetic	EM
Line of Sight	LOS
Magnetic Resonant Coupling	MRC
Radio Frequency	RF
	MPT
Laser Power Transmission	LPT
Unmanned Aerial Vehicles	UAVs
Implantable Cardioverter-Defibrillator	ICD
Computer-Aided Design	CAD
Direct Current	DC
Transmitter	Tx
Receiver	Rx
Inductive Coupling Wireless Power Transfer	ICWPT
Printed Circuit Board	PCB
Inductive Coupling Wireless	ICW
Magnetically Coupled Resonant Wireless Power Transfer	MCRWPT
Printed Spiral Coils	PSCs
Side-Lobe Level	SLL
Voltage Standing Wave Ratio	VSWR

CHAPTER 1

INTRODUCTION

Wireless Power Transfer (WPT), or Wireless Energy Transmission (WET) is a point to point energy transfer through air without using wires or cables. This technology helps the researchers and engineers to have more freedom in designing several systems in different areas of industry, biomedical, healthcare, space applications, satellites, and so on. Life has increasingly become easier and more liberated for the recent generations. The appliances which are nowadays utilized by people might have never imagined by them a century ago. Individuals are seeking more flexibility and motion; hence wireless devices are becoming more desired. Wireless communication has vastly being studied in the last decades. The idea of transferring power without the need for wires and cables has not sufficiently investigated until the last couple of decades tough. When Nicola Tesla introduced the idea of wireless power transfer, not many people invested enough trust in his efforts since they were not insightful to be cognizant of the concept. Years passed until researchers started to devote time to probe into this field of science. The emergence of new material composites also helped develop more competent batteries, another assisting resource for WPT. It helped enjoying more low-profile devices. After all the efforts, still one challenge has not efficiently being addressed. All the devices should be connected to a wall-mounted power outlet.

Many efforts have been done to down-size the chargers, but the problem of mobility is still in question. That’s where WPT becomes a pivotal matter. The liberty supported by WPT is an element which makes it more attractive for the researchers.

1.1. Objectives of the Thesis

The efficiency of WPT has long been the center of attention for the researchers. Several methods have been implemented to further improve the WPT systems. The market for power transfer is booming due to WPT's use in automotive and medical applications, specially, because of its usefulness in autonomous driving. The motivation of this thesis is to increase the efficiency of power transfer in microstrip antenna system. The objective of this thesis is to design a single triangular microstrip patch antenna using CST Microwave Studio software. Then a 2×2 antenna array will be designed to improve the efficiency of power transfer. We will design a single triangular antenna and improve the transmit efficiency compared to a couple of other works.

1.2. Wireless Power Transmission

WPT is the power transfer technology through air without the use of physical cords. The technology to support WPT was limited at the end of 19th century; hence, transferring power omitting cables could not be realized [1]. WPT is a technology used by one or more transmitters to transfer power through to one or more receivers to be stored or used in power electronic devices. The first recognized practical case of WPT was conducted in Auckland University which was of Inductive power transfer (IPT) type [2]. The next realizations of WPT are studied mostly in the 21st century. The next outstanding work was conducted by a team at MIT in 2007. A coil was used and an efficiency of 40% was acquired to transfer 60 Watts at 2 meters [3].

Today, WPT is a reality. Cellphones, medical implanted devices, electric vehicles, and many other devices are being charged wirelessly. For instance, in rotary systems such as electrical generators, alternating current, packaging machinery, wind turbines, and many other similar systems, mechanical slip-rings have shortened life span due to erosion. WPT can be a solution to the abovementioned problem with the erosion.

1.2.1. WPT Methods

There are several methods to deliver the energy wirelessly. In general, it can be categorized into two main group: Far-field and Near-field. Near-field method itself can fall into four class including EM radiation, Inductive Coupling, Capacitive Coupling, Magnetic Resonant Coupling. On the other hand, Far-field methods can be classified into two parts: Microwave Power Transmission and Laser Power Transmission. The classification scheme of WPT methods is shown in Fig. 1.1. All six subclasses in terms of the method of implementation, efficiency, distance, power limitations, and safety are compared in Table 1.1. The method that will be used in this thesis falls in the Near-field class and EM Radiation subclass. In the next six subsections we will discuss the different abovementioned methods briefly before we provide more information and examples in the next chapter.

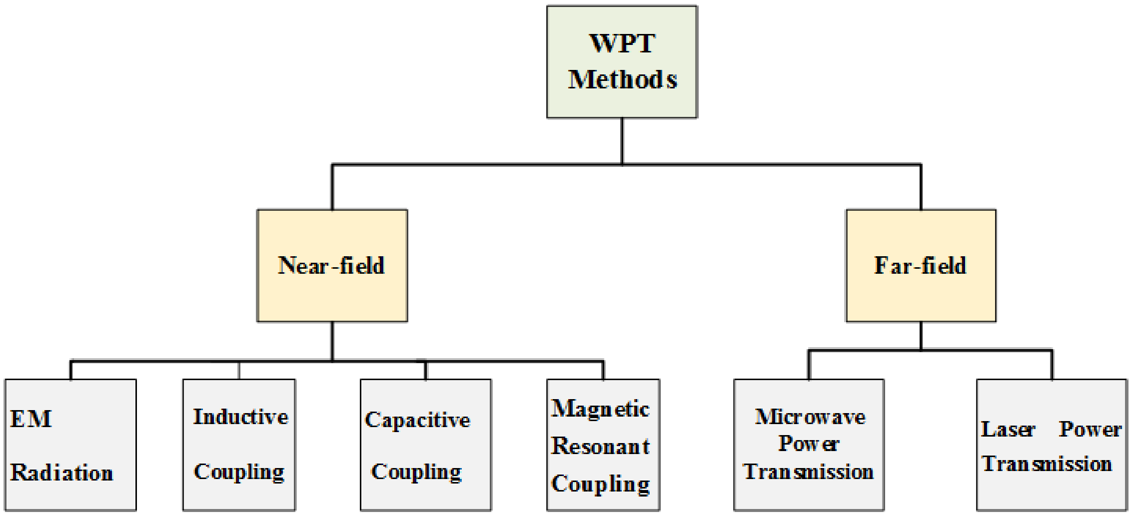

Fig. 1.1. **The diagram representing different classes of WPT**

Table 1.1: **Performance Comparison of Different Methods of WPT**

WPT Methods	Near-Field/ Far-field	Method	Efficiency	Distance	Power	Safety	Reference
Electromagnetic (EM) Radiation	Near-field	Antenna	Low to high	Short to long	Low to high	EM	[4]
Inductive Coupling	Near-field	Coil	High	Short	High	Magnetic/ confined to a small area/	[5]
Capacitive Coupling	Near-field	Capacitor	Good	Short	Low to high	Magnetic/ confined to a small area	[6]
Magnetic Resonant Coupling	Near-field	Resonator	High	Medium	High	Evanescent	[7]
Microwave Power Transmission (MPT)	Far-field	Antenna	Low to high	Short to long	Low to high	EM	[8]
Laser Power Transmission	Far-field	Laser	Low	Long	High	Laser	[9]

1.2.1.1. Electromagnetic Radiation

Energy is emitted from a transmitter antenna to a receiver one through EM waves. The antennas can be either omnidirectional or unidirectional. While omnidirectional antennas are good for information and communication purposes, they are not highly efficient for power transfer. Very low power transfer efficiencies are reported for omnidirectional antennas [10]. When there is no blockage in the Line of Sight (LOS), unidirectional antennas can be efficiently used to transfer the power especially in high-power cases. A typical EM system is shown in Fig. 1.2.

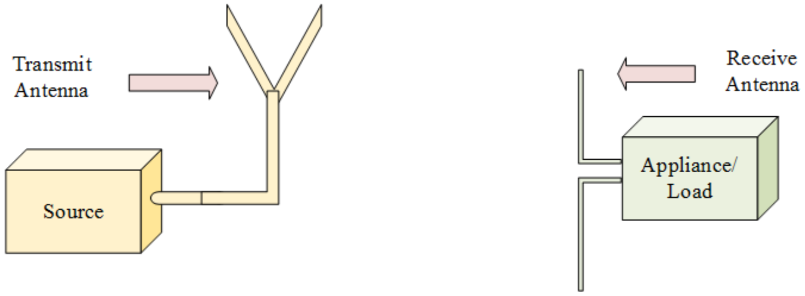

Fig. 1.2. **Electromagnetic Radiation System**

1.2.1.2. Inductive Coupling

Magnetic inductive coupling is the induction of a voltage in a conductor by alternating the current in the main conductor, mostly accomplished using coils. Faraday's law of induction describes how a varying electric field generates a time-varying magnetic field. The coils interact wirelessly in a way that an alternating current flow in the primary coil produces a time-varying magnetic field in the secondary coil which is the source of a voltage across the ends of the wire of the coil. The advantages of this method are simplicity, safety for both the system and the living beings, and uncomplicated design procedure. Figure 1.3 shows a typical inductive coupling configuration.

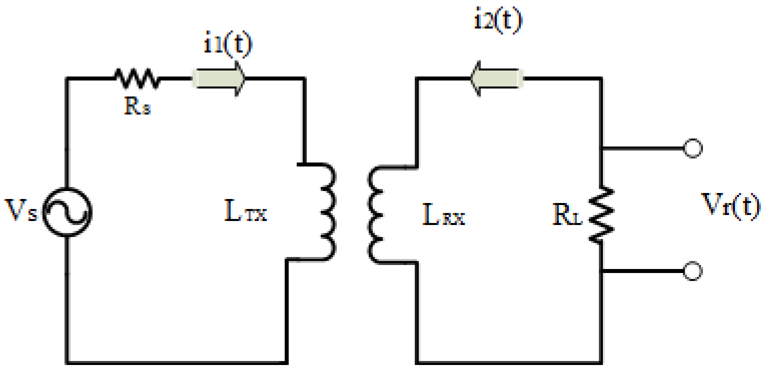

Fig. 1.3. **A typical Inductive Coupling configuration [11].**

1.2.1.3. Capacitive Coupling

The energy transfer can be achieved using electric field rather than magnetic field. The duality theorem can be used to better explain how parallel plates provide energy transfer. Figure 1.4 shows the equivalent circuit for capacitive coupling. Originally, capacitive coupling was used in low-power applications like charging cellphones, biomedical sensors, medical implants, and other small devices. Unlike magnetic field, electric field in high levels is capable of interacting with most of the materials as a result of dielectric polarization which can be very hazardous to the human body. However, recently, capacitive coupling is proven to be usable in charging a vehicle driving by a kilowatt power amount [12].

Advantages that capacitive coupling has over inductive coupling include having a confined field between the plates and no need for alignment between the transmitter and receiver [13].

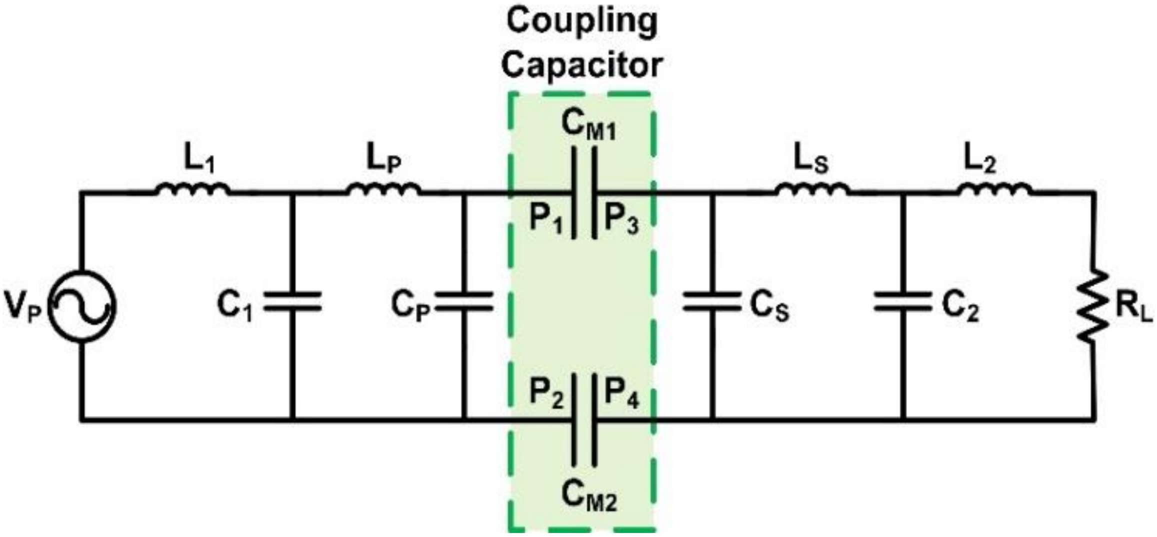

Fig. 1.4. **Equivalent circuit for capacitive coupling [14]**

1.2.1.4. Magnetic Resonant Coupling

Magnetic Resonant Coupling (MRC) was first introduced by Kurs et al. to create a strong connection between the transmitter and the receiver and benefits from inductive coupling and resonance simultaneously [3]. MRC provides longer-distance or mid-range power transfer compared to IPT. Moreover, it provides higher efficiency in mid-range compared to microwave power transfer in a similar range since the RF and rectifier efficiency lessens as the frequency increases. However, even using MRC cannot provide high efficiency which is limited to several times the size of the resonator. This problem can be addressed by implementing the MRC as relays. A relay resonator can assist power transfer [15]. An equivalent circuit of MRC system is displayed in Fig. 1.5.

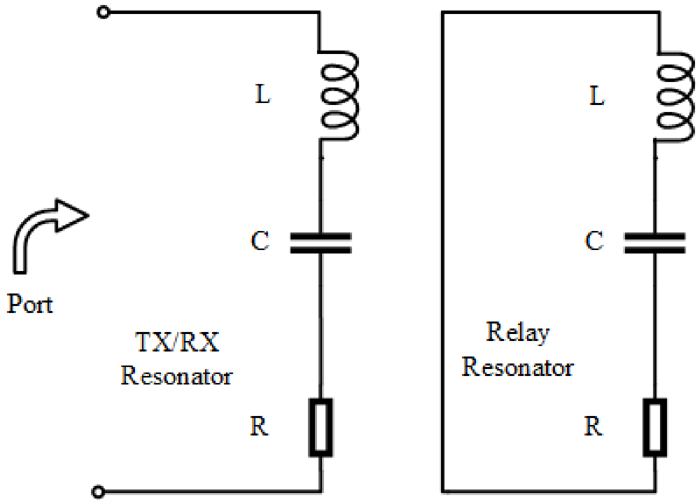

Fig. 1.5. **Equivalent circuits of TX/RX resonator and relay resonator [15]**

1.2.1.5. Microwave Power Transmission

In this method, a high power transmitter emits the power from a base station to one or more receivers. The two should be in each other's line of sight. Microwave Power Transfer (MPT) offers a satisfactory efficiency. The downside is it is difficult to have a highly focused beam at the receiver. However, there are some advantages associated with this method. It can penetrate and travel outside the atmosphere making it suitable for satellite-based power transfer. Generally. MPT uses antennas to provide the power transfer. The transmitter converts the electrical energy to electromagnetic microwaves and propagates them. In the receiver end, the receiver transforms the electromagnetic energy back to electrical energy using rectennas [8]. The diagram of a MPT system is shown in Fig. 1.6.

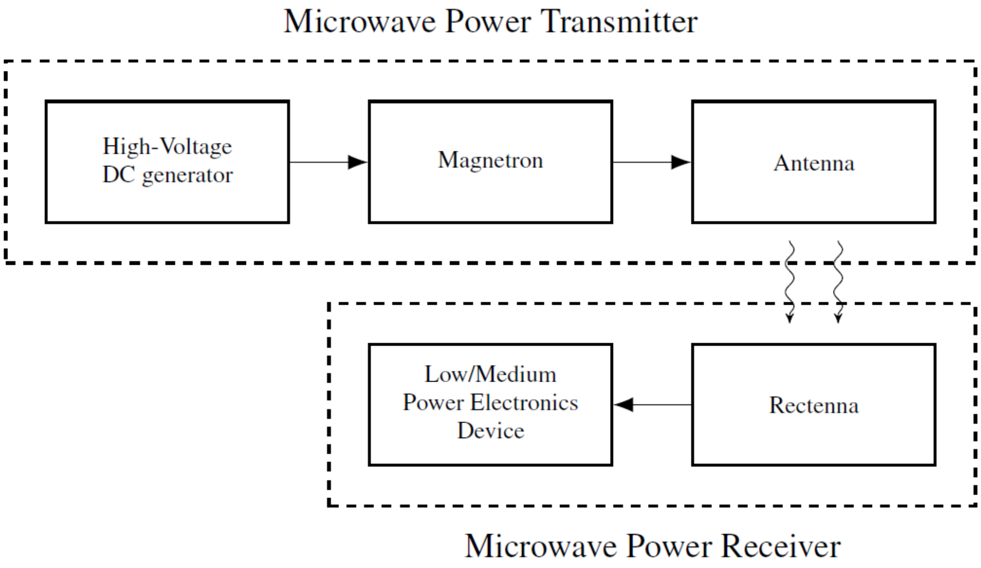

Fig. 1.6. **Schematic diagram of a MPT system [1].**

1.2.1.6. Laser Power Transmission

Perhaps the most novel method of power transmission is the Laser Power Transmission (LPT). It carries coherent and non-scattered high-level power. Though, the low efficiency limits the high power application of LPT [16]. Laser beam attenuates upon entering the atmosphere, but still it can be used outside the earth atmosphere making it desired for space discoveries. Applications which include interaction with human being should be carefully studied and investigated due to the hazardous nature of laser beam and its effects on human beings [9]. An example of a laser WPT system is shown in Fig. 1.7.

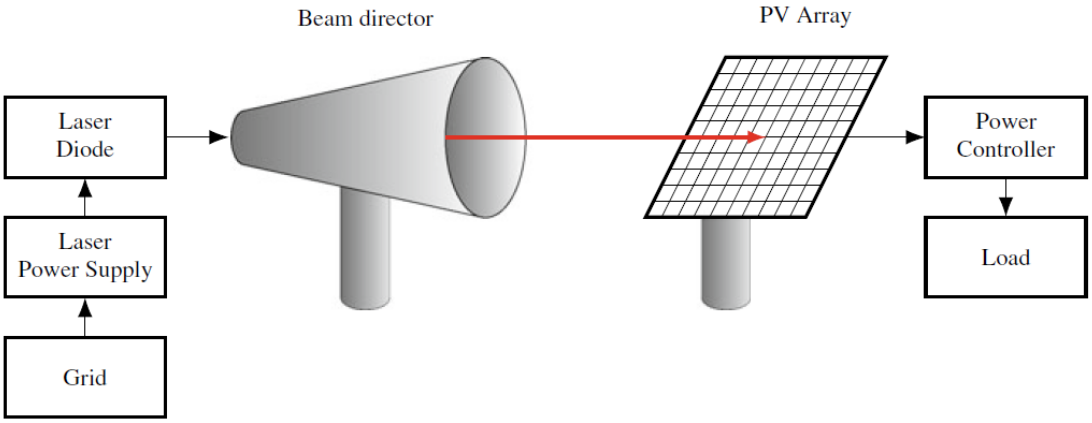

Fig. 1.7. **A typical laser WPT system [1]**

1.2.2. WPT Applications

The range of applications of WPT are vast including the following ones:

1. Moving objects:

Moving objects such as drones, Unmanned Aerial Vehicles (UAVs), robots are being used in various fields. Especially, UAVs are used in photography, transportation, and many other applications. Nevertheless, charging them is burdensome due to a limited battery life. WPT is considered a proper solution to this complication. Inductive power transfer has been investigated to charge UAVs wirelessly and good results are obtained [11]. Charging can be done in a charging station and an energy receiving device planted on the UAV [11].

2. Medical sensors and biomedical devices:

Biomedical devices are being used to save lives and charging them can be problematic since some of them are implanted inside the body. This makes the charging process very inconvenient. For instance, implantable cardioverter-defibrillator (ICD) is a battery-operated device to defibrillate, and recently pace the heart. The battery can last 6 to 10 years. However, ICD is a permanently implanted device. To replace the battery, ICD should be accessed through surgery. If ICD is charged through WPT, then there is no need to do a surgery and extra expenses can be avoided. Moreover, cardiac pacemakers, hearing aids, cochlear implants, and many other life-saving devices can be charged wirelessly too [17].

3. Easy and Clean Installation:

Wall-mounted TVs and home theaters are very popular. They give the people the benefit of having a small cinema in the comfort of their home. At the same time, the cables hanging around the TV are not very pleasant to the eye of the users. This problem can be addressed using WPT too. Similar to cellphone wireless charging, TVs, kitchen appliances, lights, and many other devices at home can be charged wirelessly. In addition to home-based applications of WPT, there are many industrial applications to eliminate cables and wires. As mentioned before, rotary systems can be a good example of such application.

In the next section, we will discuss microstrip antenna and explain why it is advantageous to use it for WPT.

1.3. Microstrip Antennas

The devices that are being used in everyday life or for medical and industrial purpose are becoming smaller and more compact. For power transfer, a more small-scale structure is desired. Microstrip antennas can provide this benefit. Microstrip Antennas were introduced in 60's [18] . In the last couple of decades, it has been more attractive for the researchers because of its thin, low-profile, lightweight, conformable, and compact features. Moreover, simple fabrication process, and integrating with other devices are other interesting characteristics of the microstrip structures. On the other hand, it has some drawbacks, narrow-bandwidth being the most important one among them. The other disadvantages of microstrip antennas include high levels of cross-polar radiation, and low-power delivery. Efforts have been made to improve some of these features and are still going on [19]. Figure 1.8 shows a microstrip patch with maximum radiation in the broadside direction ($\theta = 0$).

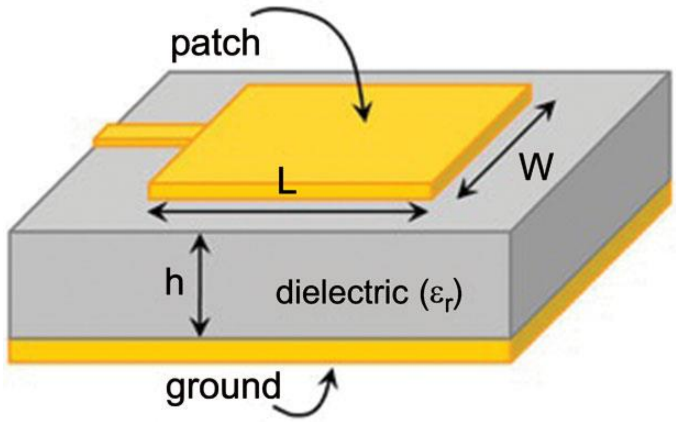

Fig. 1.8. **A rectangular metal patch placed on a dielectric grounded substrate [20].**

Many numerical techniques have been introduced to model the microstrip antenna along with Computer-Aided Design (CAD) tools including various software such as Ansys

HFSS, CST Microwave Studio, COMSOL, and many others. The important factors to consider in designing a microstrip antenna is the dimension, the substrate and its characteristics, and feeding techniques. When choosing the substrate, the relative permittivity, height, and dimension should be considered. Some of substrates being used commercially are listed in Table 1.2; however, there are many other substrates from various companies to select from. Loss factor, tan δ, is a measure of energy dissipation and is provided for each substrate in Table 1.2.

Table 1.2: **Some Common Substrates and Their Characteristics**

Manufacturer	**Substrate**	**Frequency Range (GHz)**	**ε_r**	**tan δ**
Rogers	Duroid® 5880	0-40	2.2	0.0009
Rogers	RO 3010	0-10	10.2	0.0022
Rogers	RO 4350	0-10	3.48	0.0037
MARUWA	Alumina	< 10	9.8	0.001 at 1 MHZ
DuPont™	Teflon/PTFE	> 5	2.1	0.0004
NEMA	FR4	1-10	4.4	0.030 at 1 GHz

Deciding on which substrate to choose, one should keep in mind that thicker substrates with lower dielectric permittivity provide better bandwidth and efficiency at the expense of a larger size and higher dielectric losses. In circuit applications, higher dielectric permittivity is more desirable since the electromagnetic field is confined to a small area, yet suffering from low bandwidth and high levels of dielectric loss [21].

There are different shapes of microstrip patches. Rectangular, triangular, star, circular patches are among them [22]- [23]. A star-shaped patch can be seen in Fig. 1.9.

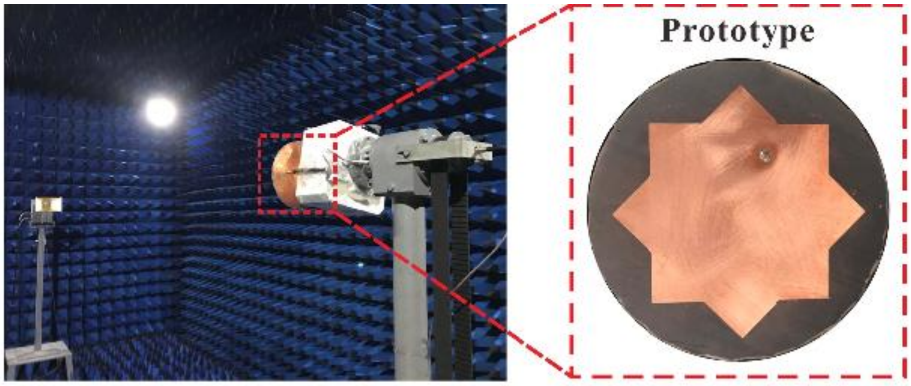

Fig. 1.9. **A star-shaped microstrip patch [24].**

1.3.1. Feeding Methods of Microstrip Antennas

Feeding techniques are diverse such as Microstrip Line [25], Coaxial cable (Probe) [26], Aperture coupling, and Proximity coupling. The microstrp feed line is a narrow strip compared to patch size and can be conducted both as edge or inset feeding. A rectangular patch fed by inset method is depicted in Fig. 1.10. A probe-fed rectangular is displayed in Fig. 1.11.

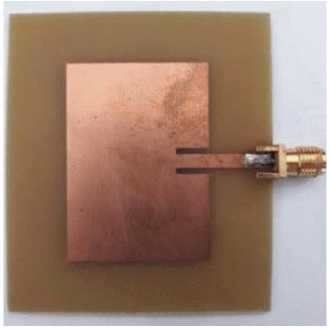

Fig. 1.10. **A microstrip-line feed [22].**

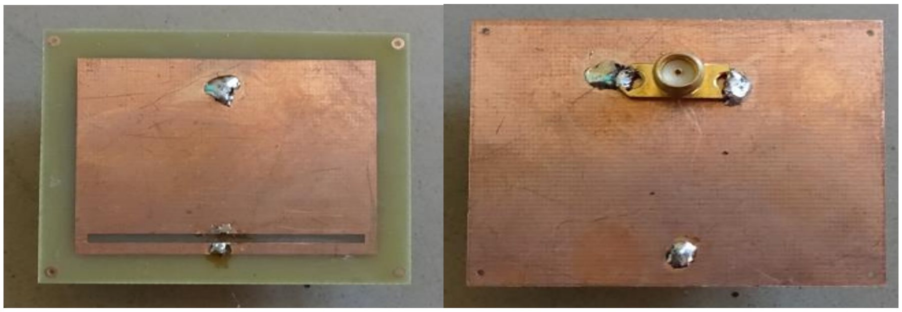

Fig. 1.11. **A Coaxial-probe feed [26].**

1.4. Array Antennas

A single antenna might not be able to deliver the desired amount of energy which is required to feed a device or instrument. Microstrip patches do not have high gain unlike horn or reflector antennas. This fact was the drive behind all the endeavors to achieve a high gain structure by using multiple individual elements. For the same reason, in this thesis we will use array configuration to enhance the performance of our single antenna. Array antennas consist of several individual elements performing as a single antenna. Single antennas are useful in some applications. Although, in WPT applications, due to the need for higher gain and directional antennas, using arrays might be a better decision. There are three different types of arrays in terms of dimension. Linear, planar, and volume arrays. The type can be decided based on the desired application. Microstrip arrays are fed in parallel or series which is shown in Fig. 1.12. Figure 1.13 shows the two-dimensional feed network.

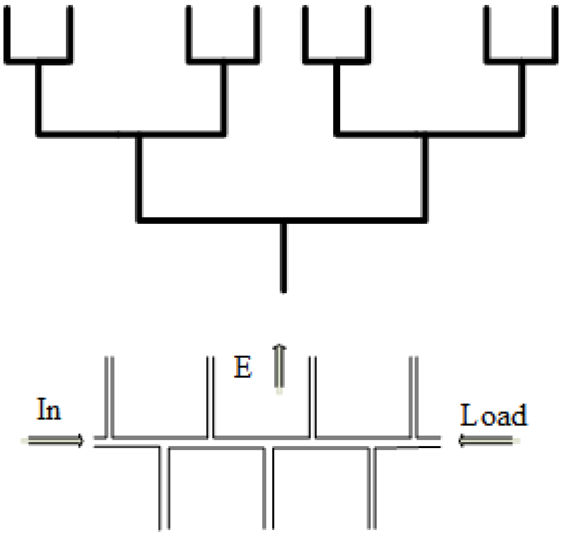

Fig. 1.12. **Rectangular patch: Parallel (top)/ Series feed network (bottom) [27]**

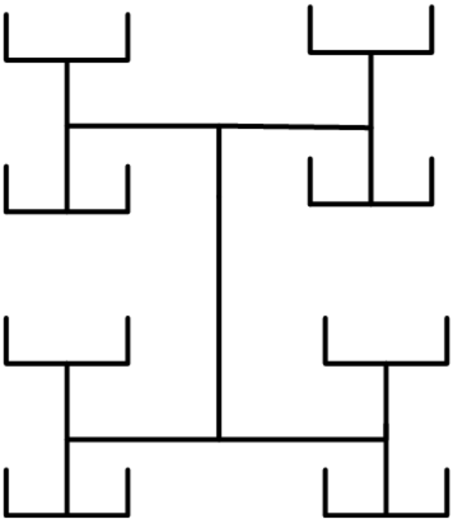

Fig. 1.13. **A two-dimensional parallel feed network [27].**

Feedlines and antennas are matched by feedline length and thickness selection along with quarter wave transformers. Each feedline should be designed in a way that finally the patches are matched to the feeding port. The patches themselves, as discussed before, can be matched to the adjacent feedline by edge-feeding or inset-feeding. Typical feedline impedances are 100, 75, and 50 Ω [27]. Advantages and disadvantages of array antennas are pointed out in Table 1.3.

Table 1.3: **Advantages and Disadvantages of Array Antennas**

Array Antennas	
Advantages	**Disadvantages**
Increase in the total gain Beamforming capability Increase in the signal strength Diversity Lower side-lobe level Improved overall performance	Higher loss due to increased resistance High complexity More troublesome implementation Increased dimension, and bulky antennas

In this thesis, we will first present the previous works done for WPT purposes. Examples of different methods of WPT will be provided. Then the method we select will be introduced. Subsequently, the single patch antenna for WPT will be designed. To better improve the gain and the efficiency, the array configuration will be proposed and its performance will be investigated and compared to a couple of previous works.

CHAPTER 2
BACKGROUND AND LITERATURE SURVEY

Wireless power transfer has recently been in the center of attention for scientist and also many companies. The automotive companies are expanding their business in Electric Vehicles (EVs) which require charging stations. The most convenient way to charge the vehicle will be wireless charging [28]. Moreover, scientists focus on WPT in order to have medical implants which can be charged wirelessly and efficiently as well as robots used for imaging or surgeries [29] [30]. There are many other applications to WPT which will be discussed in this thesis. In this chapter, previous works will be discussed and their results will be provided. As discussed in Chapter 1, there are multiple methods pf WPT. In this chapter, past works accounting for some of the methods will be presented.

2.1. Wireless Energy Transfer using Microstrip Antenna

Leong Kah Meng et al. designed a pair of microstrip antennas to be used for energy transfer [8]. The reason for selecting microstrip antenna is its unique characteristic. Straightforward analysis, simplicity, uncomplicated fabrication process and the radiation properties of microstrip patches are among them. Two antennas are fabricated at 1.94 GHz and 2.5 GHz. The performance of both antennas are evaluated considering a specific distance. The outcome proves that the antenna working at 1.94 GHz has better performance in long distances. AWR software is used to simulate the antenna. An optimization process used in the design step to account for the impedance matching since it plays an undeniable vital role in the performance of the antennas, especially in the power transfer efficiency criteria.

The dimensions of the patches has a definite effect on the resonant frequency. It can be seen that the size of the antenna for the lower frequency band is bigger than the one with higher frequency band. Figure 2.1 shows the fabricated antennas verifying the mentioned term regarding sizing.

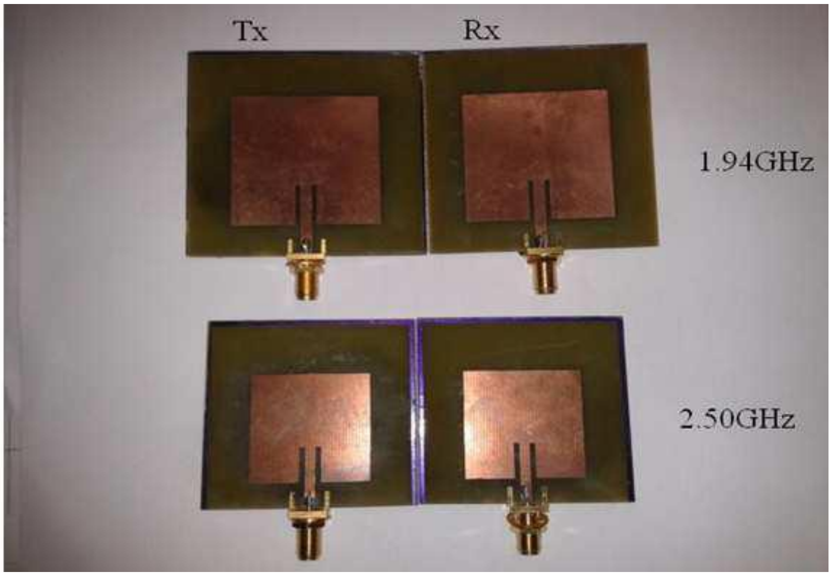

Fig. 2.1. **Fabricated microstrip antennas [8]**

The S11 parameters of the fabricated transmit antennas are shown in Fig. 2.2 and Fig. 2.3. The receive antennas have a similar S11 at the corresponding frequency. There is a negligible difference between the simulated and fabricated results.

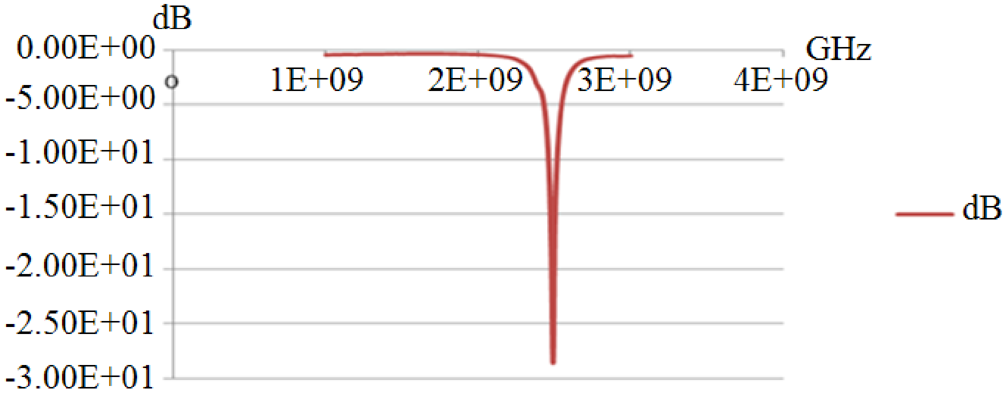

Fig. 2.2. **Transmit antenna operating at 2.5 GHz [8]**

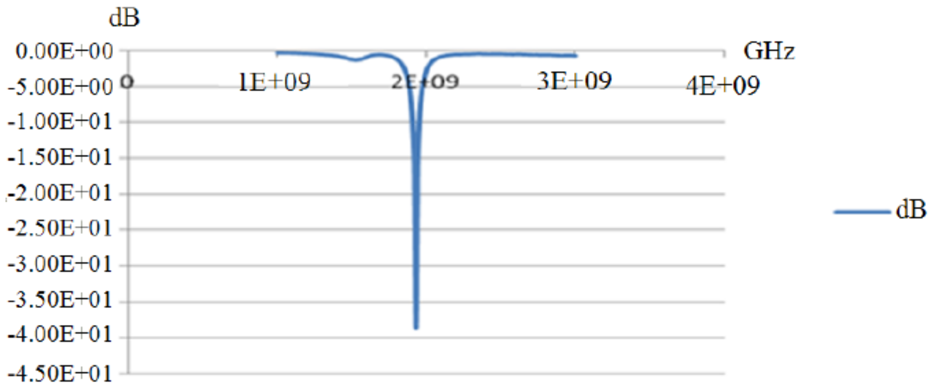

Fig. 2.3. **Transmit antenna operating at 1.9 GHz [8]**

The power transfer has been calculated in different distances to study the performance and efficiency of the structure. The distance ranges from 3 cm to 30 cm. Figure 2.4 shows the configuration used for measuring the power transfer. To avoid being affected by noise, the measurements are done twice at each frequency. Vaunix Lab Bricks RF test device which is USB powered, compact and easy to use is used for measuring along with USB Power Meter/Sensor for Mini Circuits.

A power of 10mW is transferred and the power at the receiver end is measured. It is observed that with the increase in the distance, the received power decreases in an exponential manner (Fig. 2.5). The antenna working at 2.5 GHz has a better efficiency in shorter distances. Contrarily, the power transfer efficiency in the antenna working at 1.9 GHz has a better efficiency in longer distances.

Fig. 2.4. **Measure for power received from 3cm to 30cm [8]**

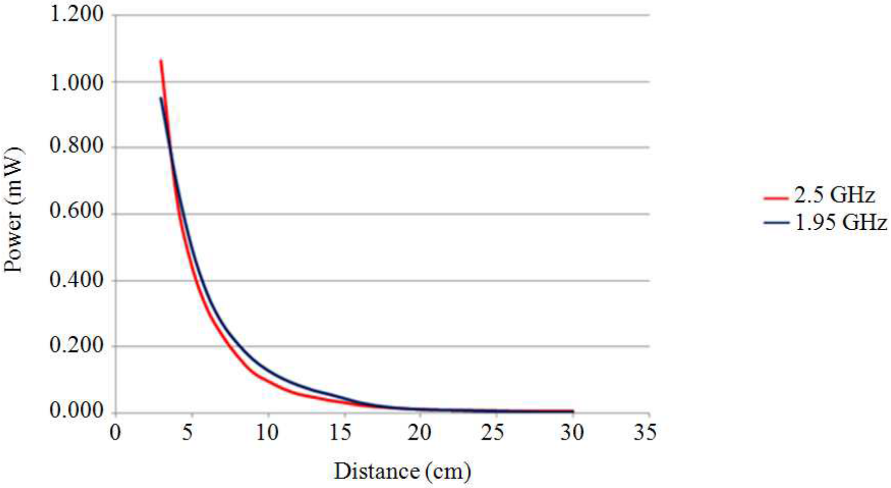

Fig. 2.5. **Received power comparison/ two different frequencies (1.94 and 2.5 GHz) [8]**

The reason behind this is the wave is bent while propagation rather than moving in a straight line. However, there are other factors in deciding the quality or efficiency of the system. The efficiency is roughly 10%. Factors effecting the low efficiency can be frequency deviation due to fabrication shortcomings, and impedance mismatch. The former can be tackled by evaluating the antenna design multiple times, and the latter can be taken care of by a proper design of the feed network.

2.2. Wireless Power Transfer in the Radiative Near-Field

This work represents a configuration for wireless power transfer in the Fresnel (or radiative near-field) zone [4]. For acceptable distances, a receiver can be placed in the diffraction-limited area, and a high power transmit efficiency is obtained. An array microstrip patch antenna is used. The receiver antenna is connected to a rectenna. Compared to a typical array, they succeeded in improving the performance by almost 67% in terms of received power. The receiver is located at the focal point which transforms the RF signal to DC using the rectifier, and read by a power meter.

A Fresnel zone is the zone between the near-field and Fraunhofer zone (or Far-field) of an antenna. The radius of the Fresnel zone is generally two times the length of antenna divided by the wavelength squared. It is in the shape of a confocal prolate ellipsoidal and in fact, there are a set of regions which fall into this definition. The whole Fresnel zone exists between the between and around a transmitter and a receiver where the main wave propagates along the line of sight (LoS).

A configuration of an aperture operating at the Fresnel region with 20 cm distancing in Fig. 2.6. In the near-field area, the waves fade away quickly as the distance increases. As long as the wave travels in the Fresnel region, the field is converged to a determined focal point, and beyond this region, the field starts to diverge. The structure consists of an 8×8 transmitter, and a 4×4 receiver. The former is edge-fed and the latter is inset-fed.

In [4], the antenna works in the radiative near-field region or Fresnel zone. The aforementioned characters are far-field characteristics. One might think that the performance of the antenna regarding these factors is not noteworthy. In fact, this is not the case, and in order to study the performance of the array antenna designed in this work, it is needed to have an understanding of the mentioned factors to investigate the array efficiency. The software used for simulation is CST Microwave Studio. The results show radiation efficiency of 86%, half-power beam-width of 7^{o}, and a gain of 23.1 dBi.

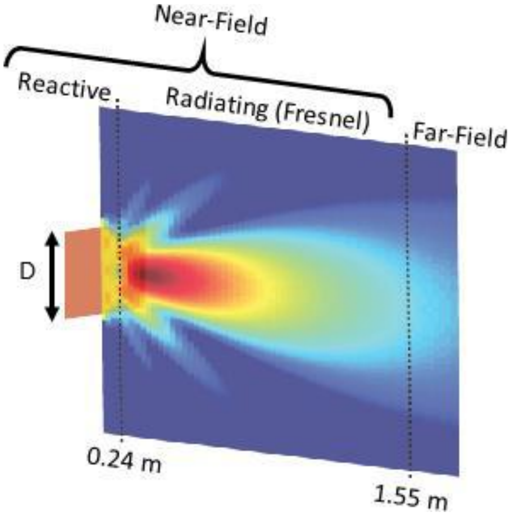

Fig. 2.6. **Fields produced by a square aperture. Focusing achieved in the Fresnel zone [4]**

The key point in designing the receiver array is to find the proper size to make sure the receiver antenna can absorb as much power as transmitted from transmitter array. Hypothetically, the proper dimension is of the order of full width at half maximum width of the field generated by the transmitter array. To avoid losing efficiency because of the spillover loss, the receiver array is considered moderately wider than the calculated dimensions to absorb the electromagnetic fields outside of −3 dB range. The receiver array is a 4×4 array of similar patches operating at 5.8 GHz. The far-field characteristics of the receiver array is as follows: the Half Power Beam Width (HPBW) is 20.7^o, radiation efficiency is 88%, and the gain is 17.7 dBi.

The structure is fabricated on a Roger 4003 substrate. The near-field efficiency of the transmitter antenna is calculated as 85% and that of receiver as 87%. The results are as reported by the simulation. The fabricated prototype is displayed in Fig. 2.7(a). The input power can reach 20 mW which can be boosted to supply up to 100 mW of power by amplification. The measurements are done by a microwave power meter.

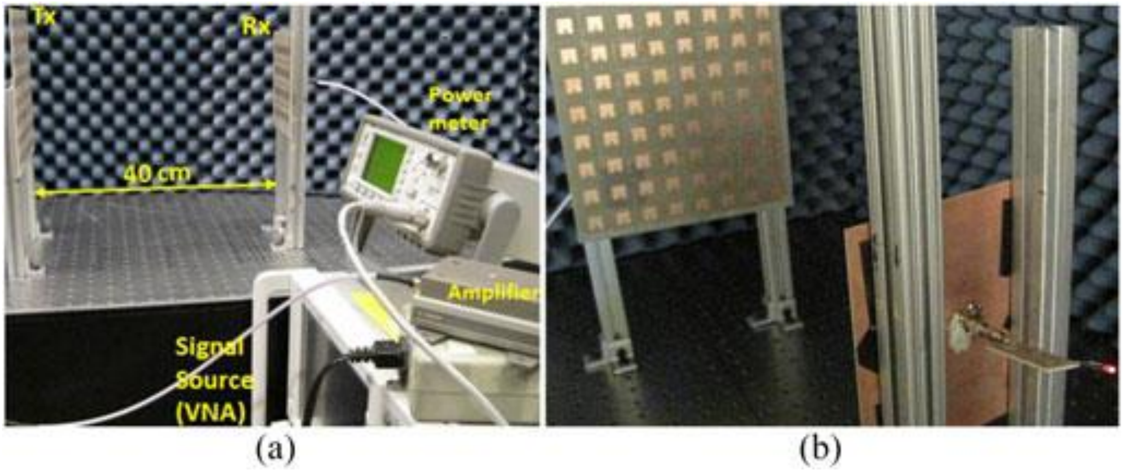

Fig. 2.7. **Fresnel WPT system. (a) Experimental setup for received power measurement (b) Powering an LED using the off-axis configuration at z = 40 cm [4]**

The type of efficiency defined in this work is in terms of the power transfer as follows (2.1):

$$\eta = \frac{P_{Rx}}{P_{Tx}} \tag{2.1}$$

As seen in Table 2.1, the Fresnel focusing improves the beamforming by 66.8%.

Table 2.1: **WPT Efficiency Values for On-axis/ Off-axis focus [4]**

On-axis		**Off-axis**
Fresnel Focus η	Beam-Forming η	Fresnel Focus η
33.2%	19.9%	24.3%

2.3. Narrow Microstrip Patches for WPT

A case of Capacitive Coupling which is included in the Near-field class is discussed in this section. The microstrip patches in [6] differs from conventional patches in terms of the width being narrower than them. The structure acts as a parallel plate capacitor. The structure enjoys a narrow capacitive area to suppress the propagated power, and focus it on the receiver.

The magnetic field is being scattered from the edges of the patch and creates a strong coupling between Tx (the transmitter) and Rx (the receiver).

Based on [31]- [32], a 100% power transfer is feasible if the transmitter and the receiver share the same frequency. However, this is not true in practice.

If the first two lowest modes are a_1 and a_2, then:

$$\frac{da_1}{dt} = -j(\omega_1 - j\Gamma_1)a_1 + j\kappa a_1 \quad (2.2)$$

$$\frac{da_2}{dt} = -j(\omega_2 - j\Gamma_2)a_2 + j\kappa a_2 \quad (2.3)$$

where a_1 and a_2 are the first and second mode amplitudes, respectively. Moreover, κ is the coupling coefficient, ω is the resonant frequency, and Γ is a demonstration of total intrinsic losses which can be defined as:

$$2\Gamma = \frac{\omega}{Q} \quad (2.4)$$

To enjoy a higher efficiency, a larger Γ is needed. Moreover, a smaller κ means a higher quality factor. Both these factors can boost the efficiency.

For near-field WPT, the non-radiating edges play a key role as well as the radiating ones since it is a main contributor to the coupling effect. This is because the microstrip patch acts the same way as the coil. As seen in Fig. 2.8, the field inside and outside the microstrip patch resembles the magnetic field around a coil. The field in the length of the patch adds to the coupling effect in near-field region which is used to transfer power to the close by receivers. Since the width of the patch is responsible for the far-field radiation, less width means there will be less field propagation to the far-field region. This makes the fields confined to the near-field region; therefore there will be higher Q factor and eventually, stronger coupling.

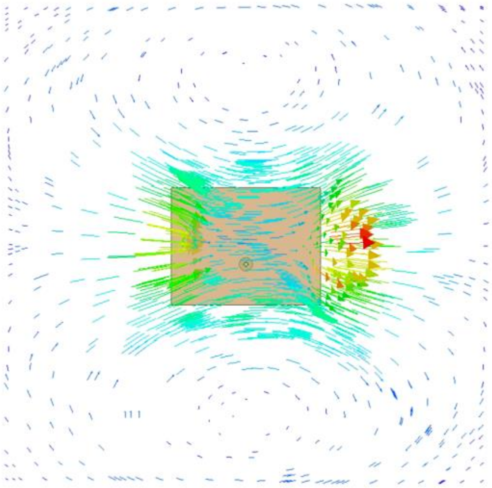

Fig. 2.8. **Magnetic field distribution in a rectangular microstrip antenna [6].**

To investigate the effect of the width of the patch on the strength of power transfer, two patches having 5 mm and 47 mm are studied (Fig. 2.9). The thickness and the length are the same.

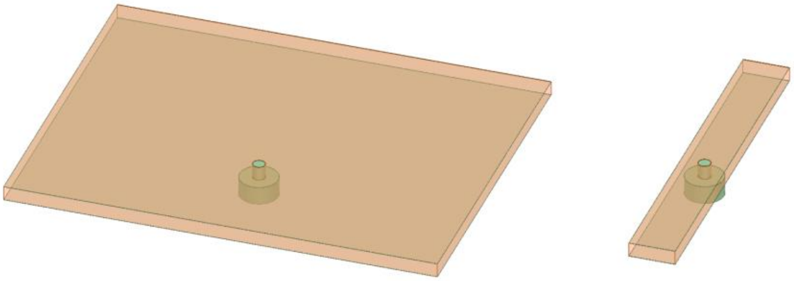

Fig. 2.9. **Left: microstrip antenna Right: radiating edge-reduced microstrip antenna [6]**

The difference between the solid lines and dashed lines in Fig. 2.10 represents the radiation efficiency of the system. As discussed above, a lower radiation efficiency can be helpful in near-field power transfer which can be seen in Fig. 2.11.

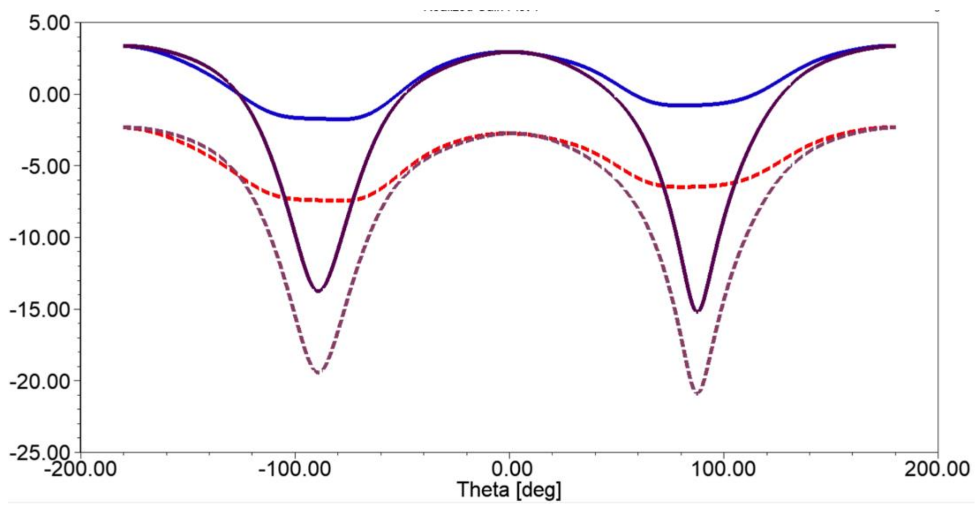

Fig. 2.10. **Directivity and gain of a microstrip antenna with a 5mm width of 5mm (solid line: directivity and dash line: gain) [6]**

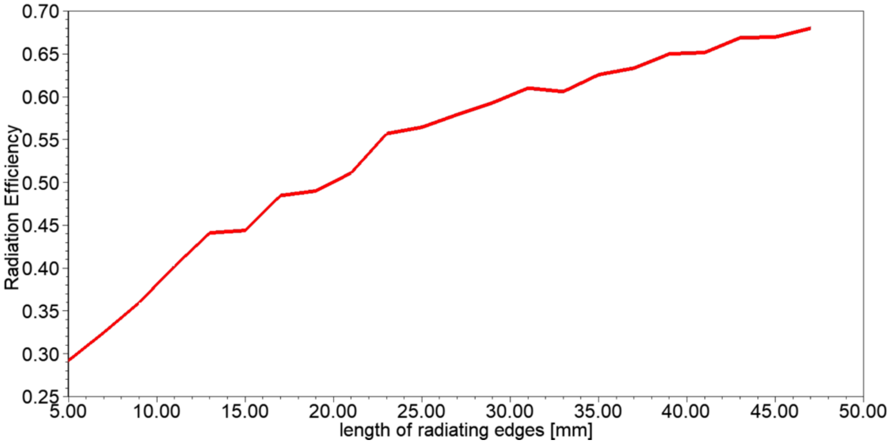

Fig. 2.11. **The radiation efficiency vs length of the radiating edges [6]**

To transmit and receive power, the same identical patches are placed in a 6 mm distance (Fig. 2.12 (a) and (b)). The result has depicted that the efficiency of the narrow system is improved from 7% to 42%. By increasing the size of the patch radiating edge, the power transfer efficiency decreases. This is due the fact that by decreasing the radiating edge, the antenna far-field radiation efficiency declines; hence, the coupling effect gets stronger and more effective. The configuration is compact, low-loss and easy to manufacture.

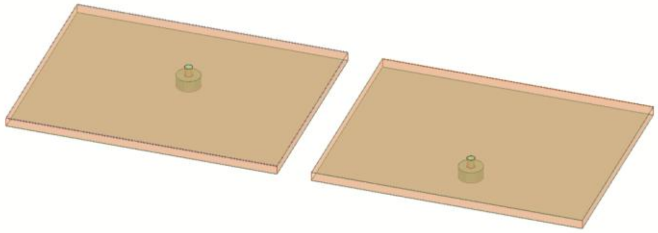

Fig. 2.12: **WPT systems with microstrip antennas.**

(a) WPT antenna system with a 47 mm width.

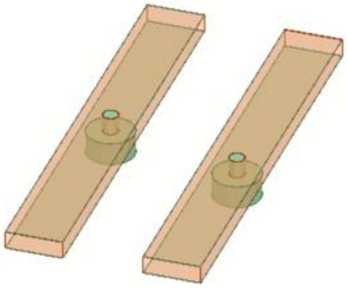

Fig. 2.12: **(b) WPT system with a 5 mm width of 5 mm [6]**

2.4. Modeling Inductive Coupling for Wireless Power Transfer to Integrated Circuits

This work is an example of Inductive Coupling WPT method. In [5], Inductive Coupling Wireless Power Transfer (ICWPT) is investigated to power ICs on a Printed Circuit Board (PCB) without the need for pins. A model is introduced and compared to the simulations of another type of inductive connection to ICs. Based on the results, as long as the ICs consume low power, the power can be provided. ICWPT is more human-friendly compared to far-field WPT since it is limited to a small area.

In case of Inductive Coupling, one of the inductors works similar to a transmitter powering the other inductor working as a receiver. The aligned coils can be seen in Fig. 2.14.

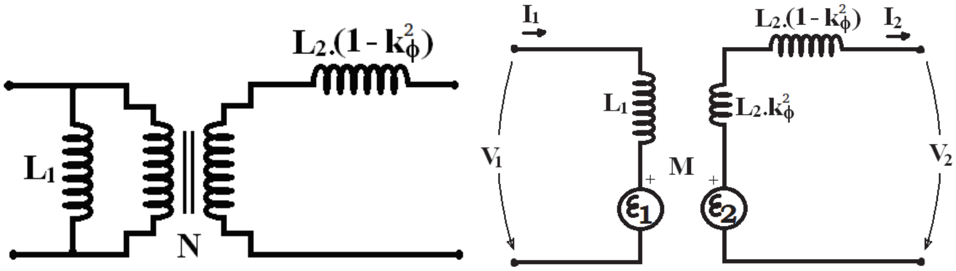

Fig. 2.13: **An example of transformer equivalent model [5]**

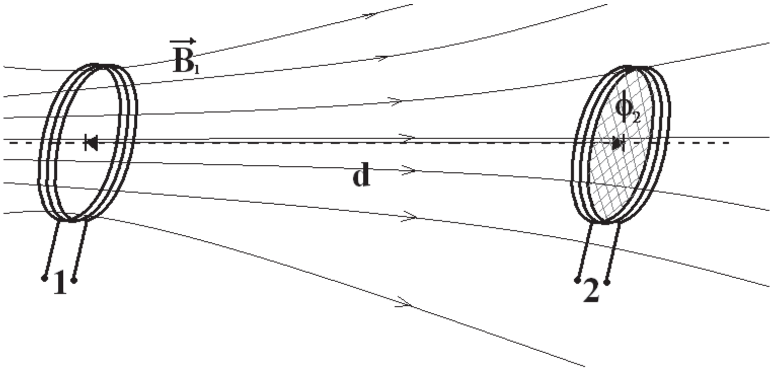

Fig. 2.14: **The aligned coils [5]**

Since planar inductors are used, the radius of each loop is different than the other loop. Therefore, the effective radius is considered. A ferromagnetic material will boost the magnetic field lines in the second coil as it focuses them in the receiver coil location. Unlike the ferromagnetic material, the conductors will decrease the strength of the magnetic field in the receiver inductor’s location. Hence, the coupling coefficient will decrease in case of conductors, and conversely, it will increase in case of ferromagnetic material.

The optimal situation is when the voltage is higher as much as the IC limitations grant at the receiver. As the frequency increases in case of a conducting core, the magnetic induction reduces. Low frequencies will contribute to a higher transformer ratio. The software used is Ansoft HFSS. The values in Fig. 2.15 can be calculated using Z-matrix.

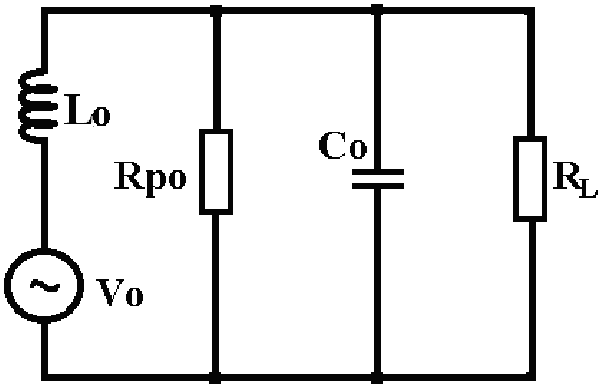

Fig. 2.15: **Inductive-based harvest equivalent circuit [5]**

It is proven in [5] that power transfer in ICs is realizable by ICWPT and a satisfactory power transfer can be obtained to power ICs. A transmitter inductor L_1 is placed beneath the FR4 substrate. A receiver inductor L_2 is placed above the IC which is affixed to the substrate (Fig. 2.16).

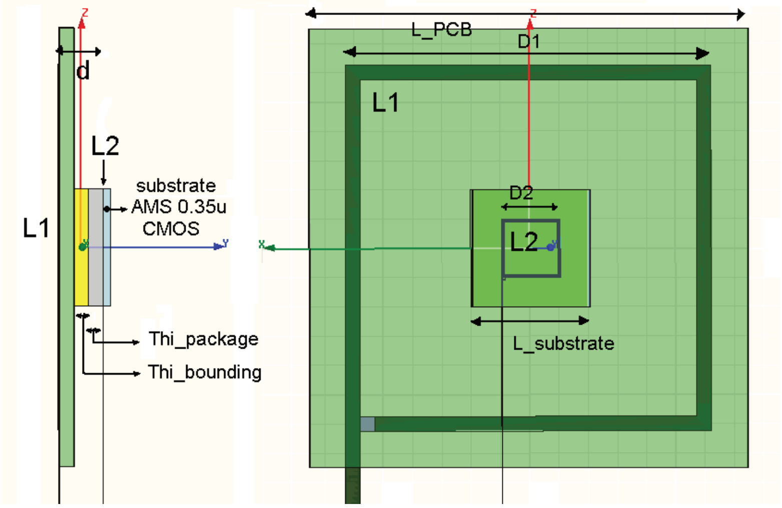

Fig. 2.16: **ICW power transfer from PCB to IC: schematic view [5]**

2.5. A Planar MCR-WPT System with Spiral Coils

A Magnetically Coupled Resonant Wireless Power Transfer (MCRWPT) planar system is introduced in [7]. Printed Spiral Coils (PSCs) are used as the planar representation of the inductors functioning to provide and utilize the power. In the next step, an equivalent circuit is obtained to ease the design process. Then, a flow-diagram is introduced to improve the system performance based on the limitations imposed on the variables. To have a higher power transfer efficiency, a number of features are studied to better understand their effect including loop quality factor, mutual coupling, input impedance, and frequency splitting. Extra strips are put in the back of the substrate and through vias are linked to the spiral coils. The mentioned method is used to decrease the resistance and improve the Q factor.

The structure consists of four elements including a drive loop, a transmitter coil, a receiver coil, and a load coil. All the components printed on FR4 substrate can be seen in Fig. 2.17. In order to have a planar system, the transmitter and driver should be close to each other. Moreover, the receiver and the resonator coil should be nearby. However, the short distance results in a stronger mutual coupling and this in turn triggers frequency splitting, and this in turn decreases the efficiency of WPT.

The equivalent circuit of the system can be seen in Fig. 2.17. It is useful in designing and acquiring the best values of the elements. After optimizing the variables, Ansoft HFSS software is used to adjust the sizes more precisely. The dimensions are provided in Table 2.2. Auxiliary strips are added to the system to improve the Q factor without increasing the size of the structure. The fabricated model can be seen in Fig. 2.18 with the number of turns equal to 2. The final results are represented in Table 2.3.

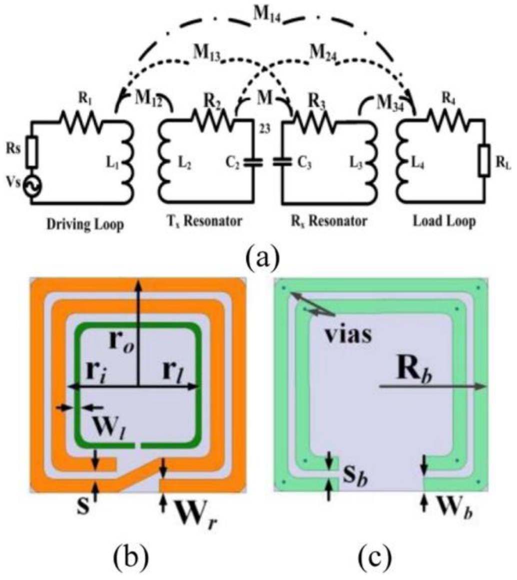

Fig. 2.17. **(a) Equivalent circuit of the introduced system. (b)Configuration of the introduced system. (c) Configuration of the system with auxiliary strips [7]**

Table 2.2: **Design Parameters [7]**

Parameter	**2-turn WPT**	**2-turn WPT with parallel paths**
W_r (mm)	4	2.5
W_l (mm)	6.3	6.3
r_o (mm)	50	50
r_l (mm)	29.5	29.5
s (mm)	3.7	3.7
L_2 (μH)	0.61	0.58
C_2 (pF)	220	240
R_S (Ω)	0.19	0.15
Q_2 (unloaded) @ 13.56 MHz	274	328
SRF (MHz)	134.25	130.2

Fig. 2.18. **The fabricated system [7]**

Table 2.3: **Transfer Efficiency of the Systems [7]**

Studied Process	**2-turn WPT**	**2-turn WPT with parallel paths**
Calculation	78.46%	-
Simulation	77.51%	81.87%
Measurement	77.27%	81.68%

The efficiency of the system is displayed in Fig. 2.19 where the analytical, simulation, and fabrication results are provided with/without auxiliary strips. The operation frequency is 13.56 MHz. In this work, a satisfactory agreement between the calculated and measurement results is met.

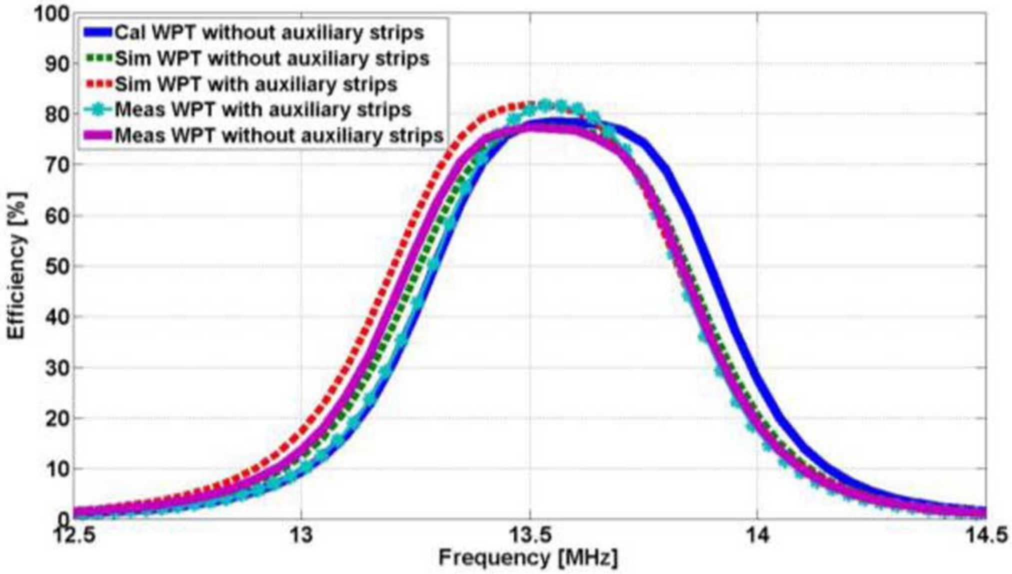

Fig. 2.19. **The results of calculation, simulation, and measurement of transfer efficiency of the introduced system at a 10 cm distance [7]**

2.6. Conclusion

In this chapter, the previous works using different far-field and near-field methods are studied and the advantages and disadvantages of them are discussed.

CHAPTER 3

PROPOSED STRUCTURE DESIGN

The selected method in this thesis is EM radiation which is used in microwave frequencies. One of the most useful and cost-effective elements used in microwave band is microstrip patch. A patch or microstrip antenna involves a metal surface on a dielectric substrate and a ground metallic surface beneath the substrate. Microstrip antennas take various shapes and dimensions. Rectangular, triangular, star-shaped, circular, ring-shaped, and square patches are among them. The triangular patch is selected. Triangular patches and their advantages and disadvantages over rectangular patches are studied in previous works. It is shown that triangular array can enjoy a similar performance to rectangular array. It is also proven that using triangular patch array can provide more suppression of side lobe level (SLL) than rectangular patch array [33]. The radiation from side lobes dissipates the energy to unwanted directions which is not favorable especially, in WPT applications as we need to transfer as much energy as we can. This fact is one of the reasons that triangular patch is used in the current thesis. The proposed structure will be operated at ISM Band which includes 2.45GHz or 5.8 GHz. The results are represented for both frequency bands.

In this chapter, the structure and dimensions of the proposed antennas will be provided. The dimensions of proposed structure and feeding network for 2.4 GHz and 5.8 GHz frequency band will be presented. The dimensions for the tilted antenna is similar to the 2.4 GHz proposed antenna, since it operates at the same frequency.

In the next step, dimensions of the patch are calculated by the following equations [34], *a* being the side length of the triangular patch:

$$f_r = \frac{2c}{3a\sqrt{\varepsilon_r}} \tag{3.1}$$

where f_r is the resonant frequency, c is the speed of light, ε_r is the relative permittivity of the substrate. Another depiction of the equation is as follows:

$$a = \frac{2c}{3f_r\sqrt{\varepsilon_r}} \tag{3.2}$$

The height of the triangle, H, can be provided by (3.3).

$$H = \sqrt{a^2 - \left(\frac{1}{2} \times a\right)^2} \tag{3.3}$$

3.1. Single Patch at 2.4 GHz

The current patch is designed to function at 2.4 GHz frequency band. The side length of antenna is $\lambda_0/2$ or 56mm. The substrate used is Teflon with 1.56mm height and relative permittivity of 2.1. To have more accurate simulation results, about 6 times of substrate height should be added to the size of patch to account for the substrate size. Dimensions of the single patch are provided in Table 3.1. Parametric study can be used to optimize the design in CST software.

The patch configuration is depicted in Fig. 3.1. The inset feeding method is used to feed the antenna.

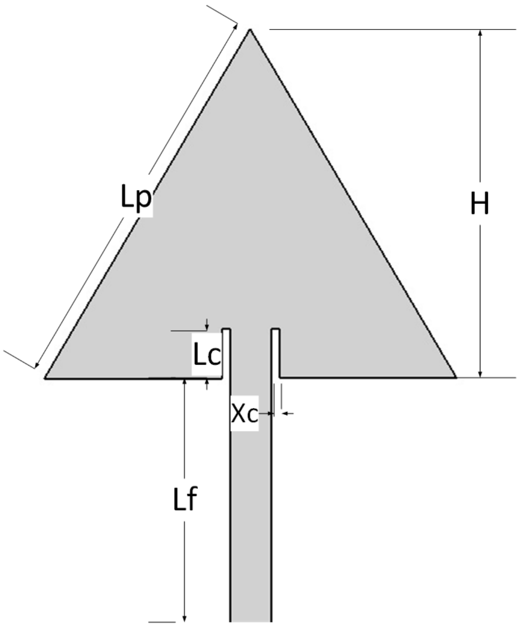

Fig. 3.1. **The structure of the single triangular patch**

Table 3.1: **Dimensions of the Single Patch at 2.4 GHz**

Single Patch	**Lp**	**Lc**	**Xc**	**Lf**	**H**
Size (mm)	56	14	0.5	30	1.56

3.2. Proposed Array and Feed Design at 2.4 GHz

The system consists of a pair of identical arrays, a transmitting and a receiving antenna which is displayed in Fig. 3.2. The reason for choosing identical arrays is the simplicity of the design and analyzing the results. Distancing between the two antennas is d. The antenna is a 4×4 array of triangular patches fed by a coaxial line beneath the substrate. The patches are fed by inset method and the coax probe is connected to the middle of the feedlines. The energy dissipation is relatively low in the current structure which leads to high efficiency of power transmission. Dimensions of the array and the feeding lattice can be found in Table 3.2. To achieve the desired characteristics of the structure, an appropriate distance should be selected. S21 or transmission coefficient describes the amount of power received at the second antenna relative to the power transmitted at the transmitter antenna. Along the *x* axis, the patches are *H*-plane coupled and along the *y* axis, they are *E*-coupled.

Several benchmarks are used in deciding the quality or efficiency of the power transfer system. An accepted one is the transmission coefficient calculated by:

$$T = 10^{(S21/10)} \times 100\% \qquad (3.4)$$

In Fig. 3.2, W50 is the width of 50 Ohm microstrip line and so on. The width and length of each micrsotrip line is calculated by Macros/ Calculate/ Calculate Analytical Line Impedance in CST Microwave Studio. Then it can be optimized to provide the best impedance matching for the structure.

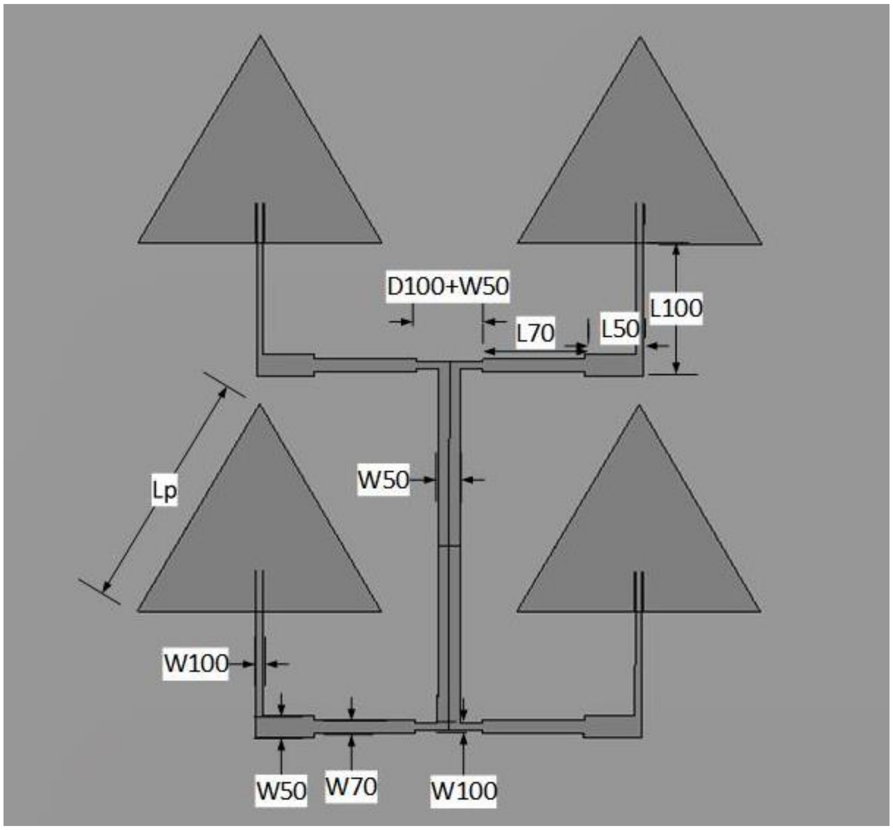

Fig. 3.2. **The structure of the array and the feedlines.**

Table 3.2: **Dimensions of the Array Antenna at 2.4 GHz**

Array Dimension	***Lp***	***L50***	***W50***	***L70***	***W70***	***L100***	***W100***	***D100***
Size (mm)	53.6	13	5	23	3	30	1.5	10

3.3. Single Patch at 5.8 GHz

Similar to the 2.4 GHz, the patch for 5.8 GHz frequency is designed and its dimension is obtained. From Eq. (3.2), the side length of the patch is 23.8 mm. From Eq. (3.3), the height of the antenna is 20.6 mm. Using the parameter sweep in CST and considering the fact that the feedlines also radiate and affect the center frequency of the antenna, the side length of the antenna is considered 20.8 mm. Dimensions of the 5.8 GHz patch are provided in Table 3.3.

Table 3.3: **Dimensions of the 5.8 GHz Patch**

Single Patch	***Lp***	***Lc***	***Xc***	***Lf***	***H***
Size (mm)	20.8	5	0.3	30	1.56

3.4. Proposed Array and Feed Design at 5.8 GHz

The array operating at 2.4 GHz might be large for some ISM applications. Especially, for the biomedical applications, a smaller system might be needed. Therefore, the array is designed at 5.8 GHz because higher frequency provides smaller dimension. We will check if the configuration has the same transfer efficiency if used at 5.8 GHz. The structure schematic is similar to Fig. 3.2.

3.5. Tilted Array at 2.4 GHz

The array consists of 2×2 elements which are 45 degree off-axis rotated. An identical antenna functions as the receiver antenna to have the best coverage between two antennas. Fig. 3.3 shows a schematic view of the tilted array. The dimensions are similar to the array at 2.4 GHz.

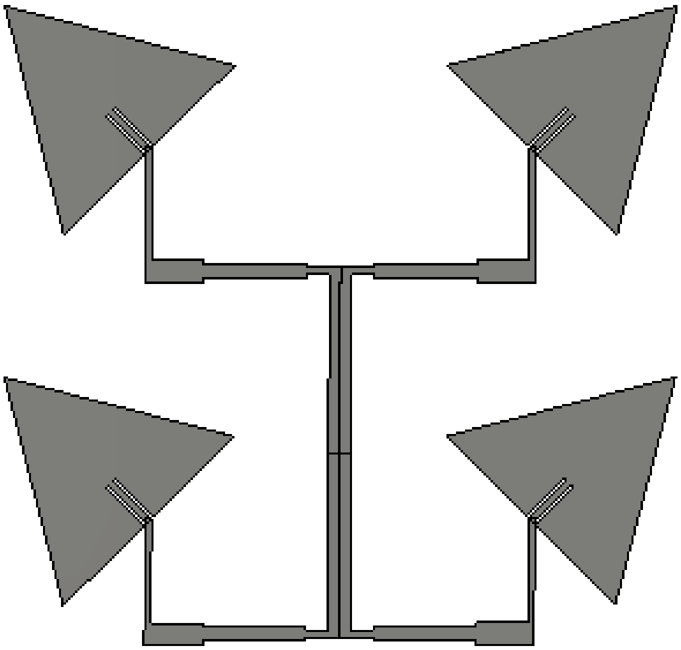

Fig. 3.3. **The tilted array configuration**

3.6. Conclusion

The structure of the antennas are shown in Fig. 3.1, Fig. 3.2, and Fig. 3.3. The dimensions of the proposed structures are presented in detail along with those of the feeding network.

CHAPTER 4

SIMULATION RESULTS

In Chapter 3, the schematic of the antennas were provided and the related parameters were introduced in terms of dimension. In this chapter, the simulation results will be provided and discussed. For each configuration and operating frequency, the reflection coefficient or S11, the transmission coefficient or S21, the radiation pattern, and the 3D radiation pattern will be provided. The results are provided in both the resonant frequency and the desired frequency in order to be able to have a meaningful comparison between the structures.

4.1. Single Patch Results at 2.4 GHz

Return loss which measures relative power of the signal reflected by a discontinuity in a transmission line should be less than –10 dB. VSWR is the ratio between transmitted and reflected voltage standing wave and the amount of −10 dB corresponds to VSWR < 2. The reflection occurs due to load and transmission line characteristic impedance mismatch. As seen in Fig. 4.1, the reflection coefficient or S11 is –30 dB at the center frequency of 2.37 GHz. At 2.4 GHz frequency, the S11 is –11.5 dB. On the other hand, the transmission coefficient which measures the power transmitted relative to the incident wave is roughly –3.5 dB at 2.4 GHz and is displayed in Fig. 4.2. The radiation pattern in Fig. 4.3 shows the gain equaling 3 dB at 2.4 GHz for the single triangular patch. The 3D pattern is depicted in Fig. 4.4.

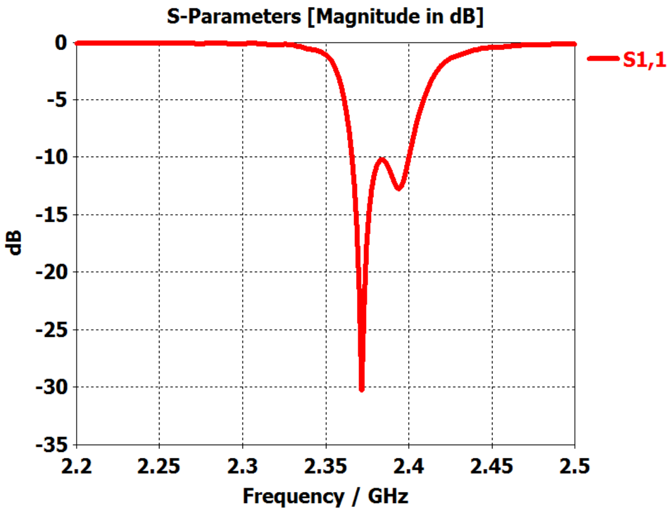

Fig. 4.1. **S11 parameter of single triangular patch antenna at 2.4 GHz**

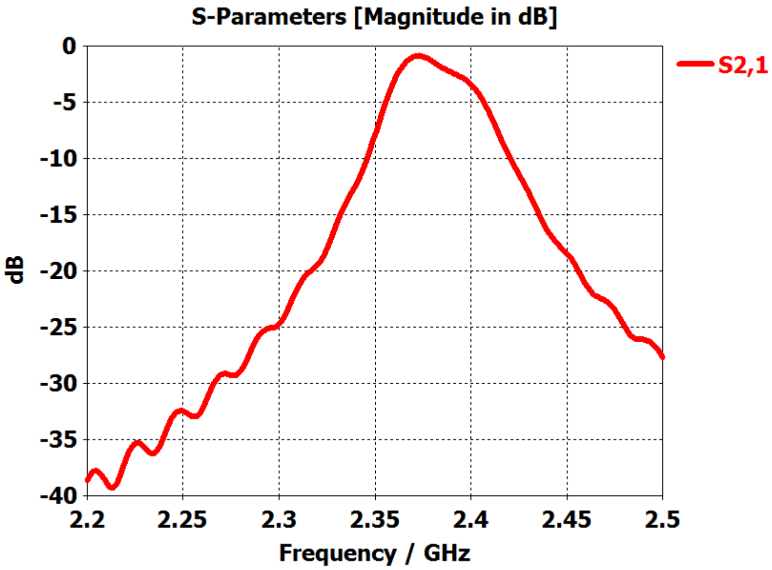

Fig. 4.2. **S21 parameter of single triangular patch antenna at 2.4 GHz**

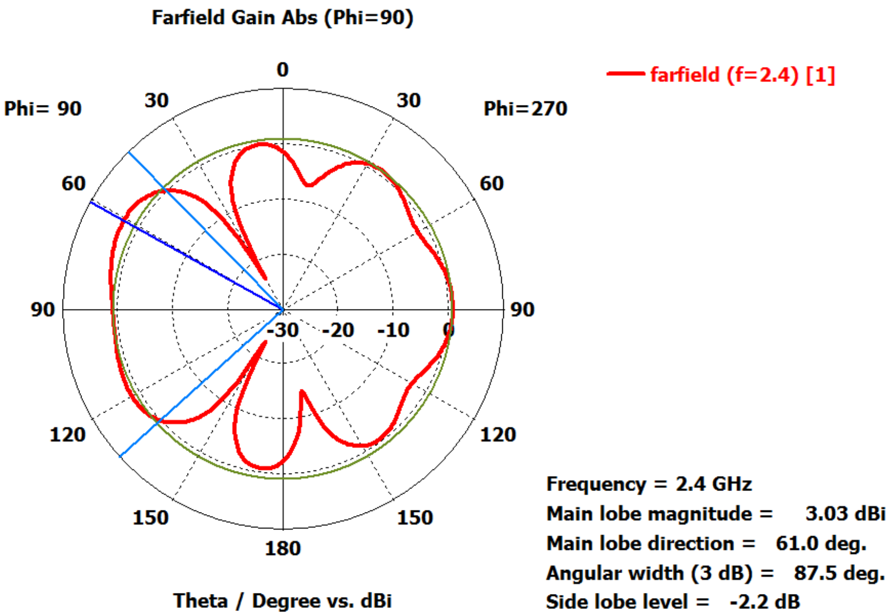

Fig. 4.3. **Radiation pattern of single triangular patch antenna at 2.4 GHz**

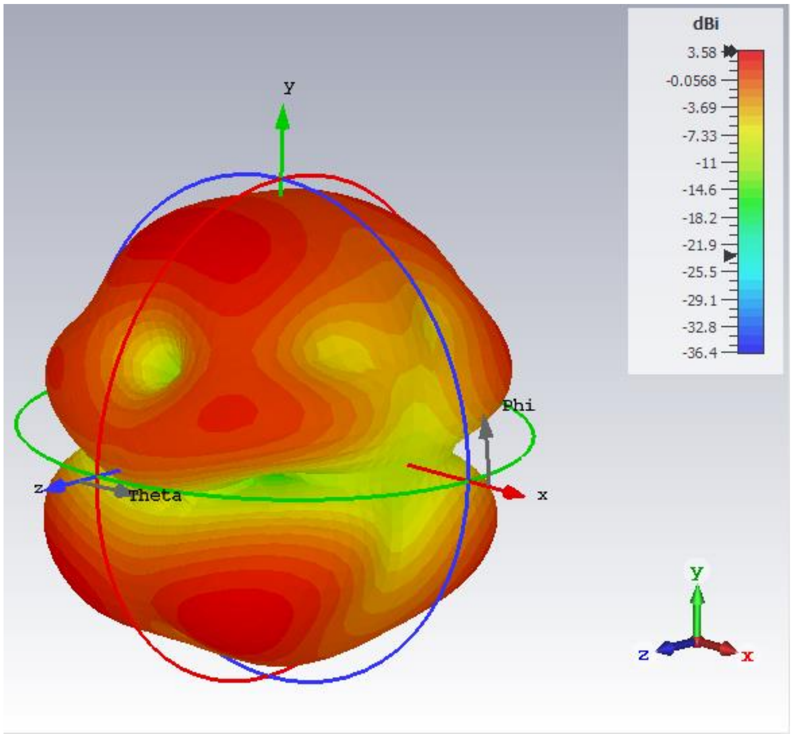

Fig. 4.4. **3D radiation pattern of the single triangular patch at 2.4 GHz**

4.2. Array Results at 2.4 GHz

The reflection coefficient for the array configuration is –28 dB at the center frequency of 2.4 GHz as displayed in Fig. 4.5. The transmission coefficient is –0.55 dB at 2.4 GHz corresponding to a power transfer efficiency of 89% at the center frequency and 50 mm distancing depicted in Fig. 4.6, compared to the single patch which offers 44% of power transfer efficiency with the same distancing and frequency band. The radiation pattern is seen in Fig. 4.7 which provides a 17.7 dB gain compared to 3 dB gain for single patch at the same frequency. Figure 4.8 shows the 3D gain pattern of the array.

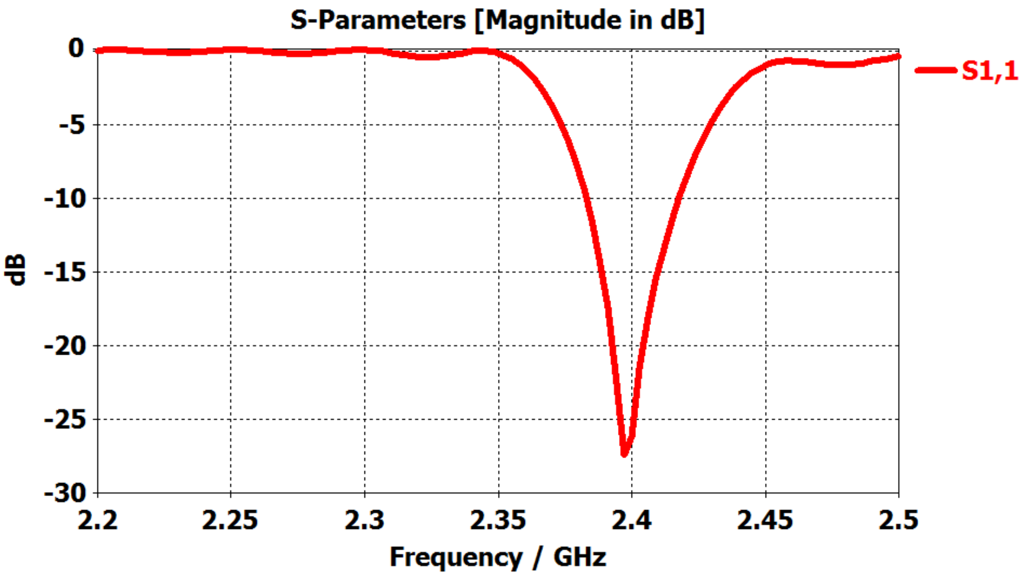

Fig. 4.5. **S11 parameter of array antenna system at 2.4 GHz**

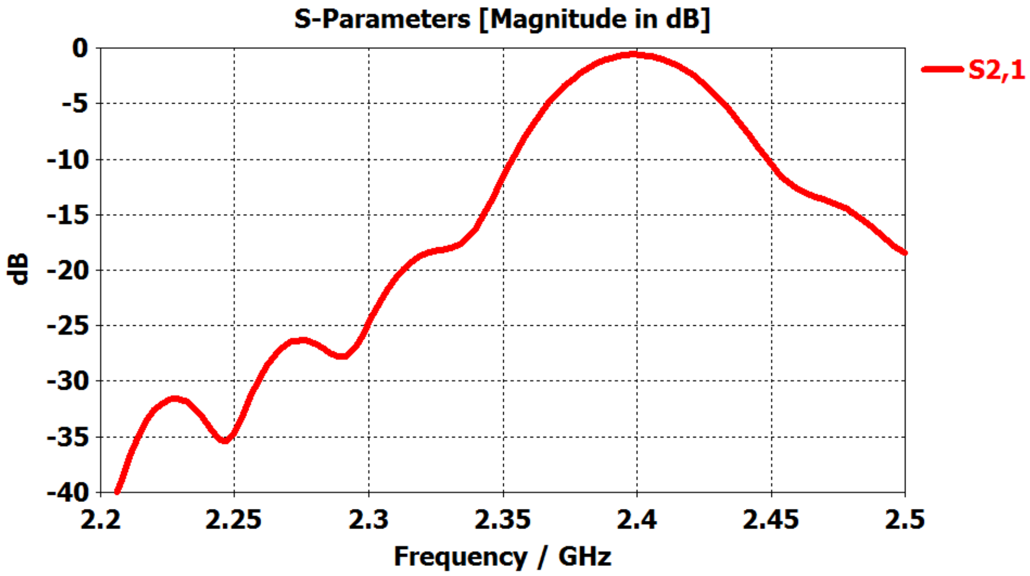

Fig. 4.6. **S21 parameter of array antenna system at 2.4 GHz**

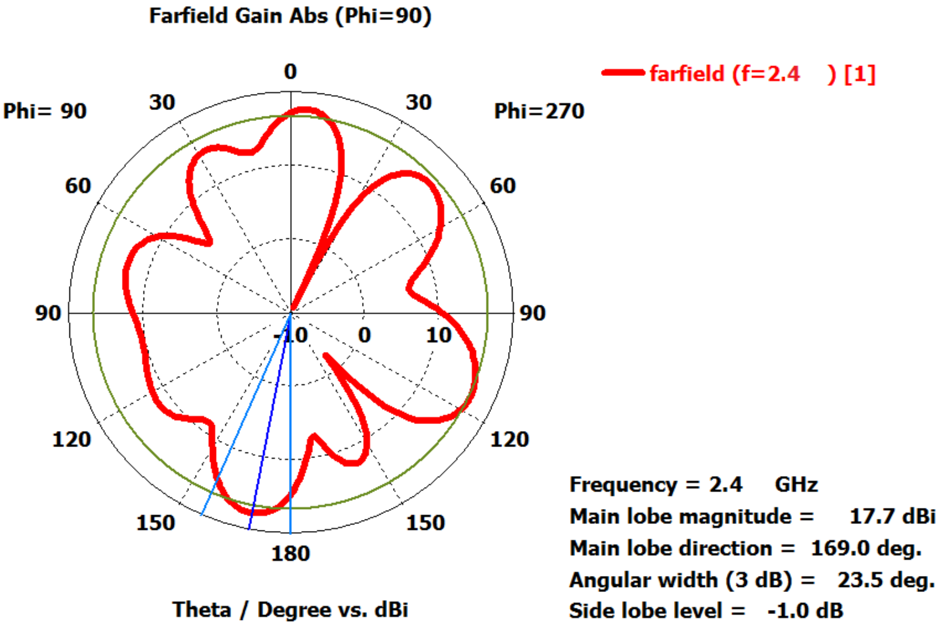

Fig. 4.7. **Radiation pattern of array antenna system at 2.4 GHz**

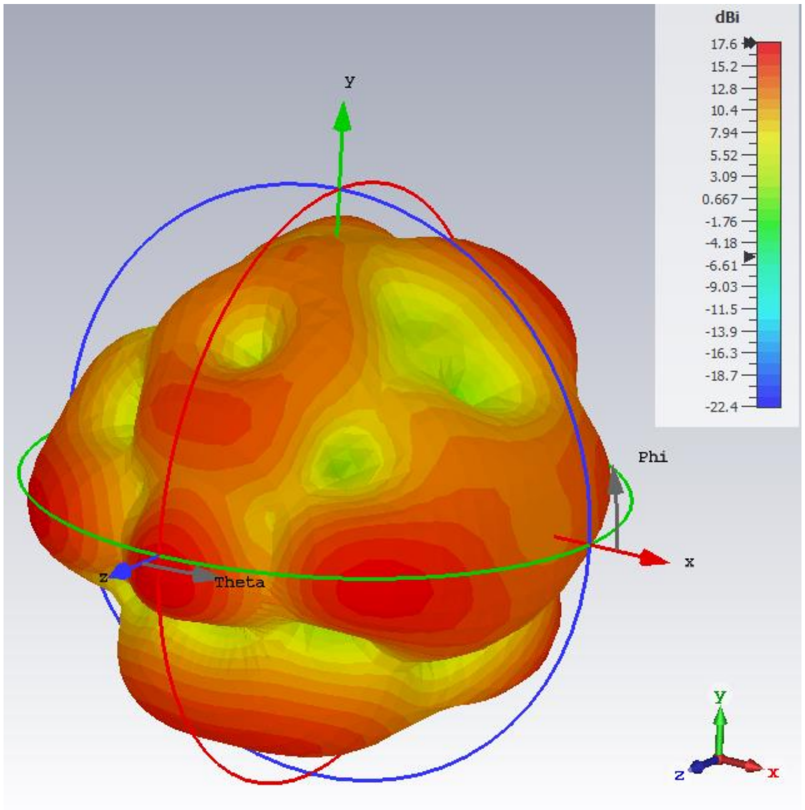

Fig. 4.8. **3D radiation pattern of the proposed array at 2.4 GHz**

4.3. Single Patch Results at 5.8 GHz

As mentioned earlier, to have a smaller system, a higher frequency can be used. The dimensions of the patch at 5.8 GHz is given in Chapter 3. The reflection and transmission coefficient is given in Fig. 4.9 and Fig. 4.10, respectively. The polar and 3D radiation pattern are shown in Fig. 4.11 and Fig. 4.12, respectively.

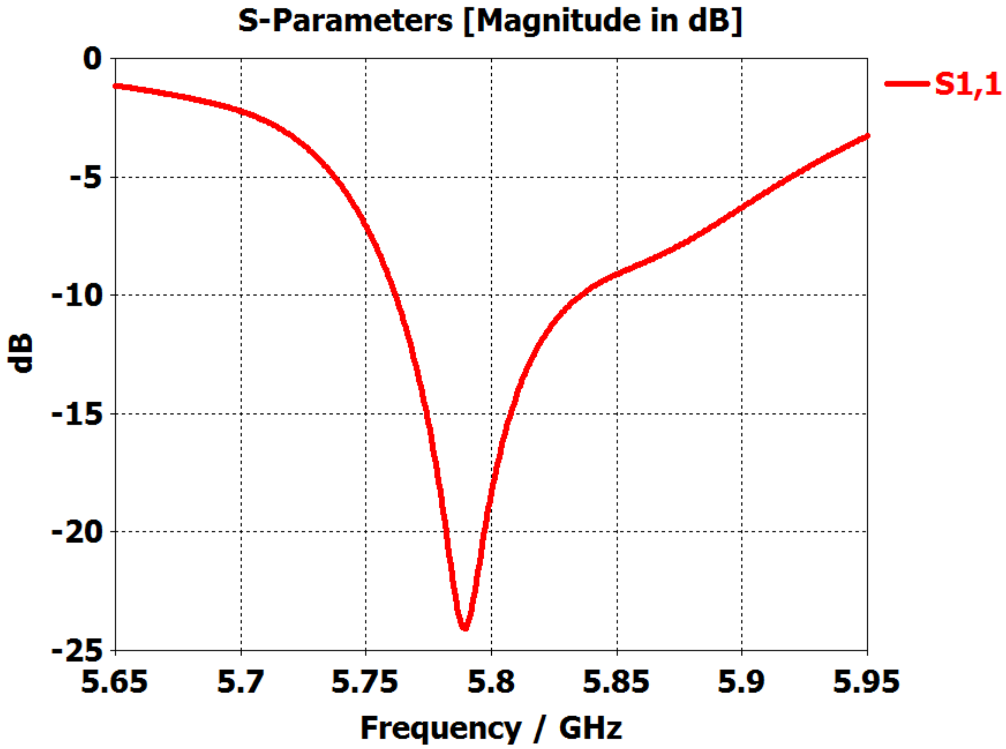

Fig. 4.9. **S11 parameter of the single triangular patch antenna at 5.8 GHz**

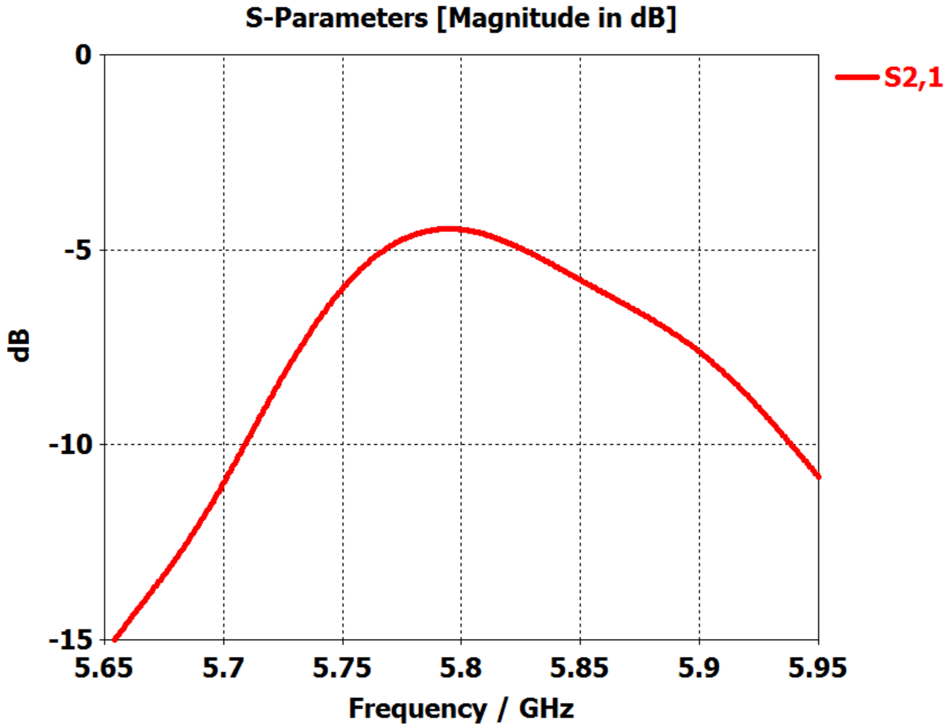

Fig. 4.10. **S21 parameter of the single triangular patch antenna at 5.8 GHz**

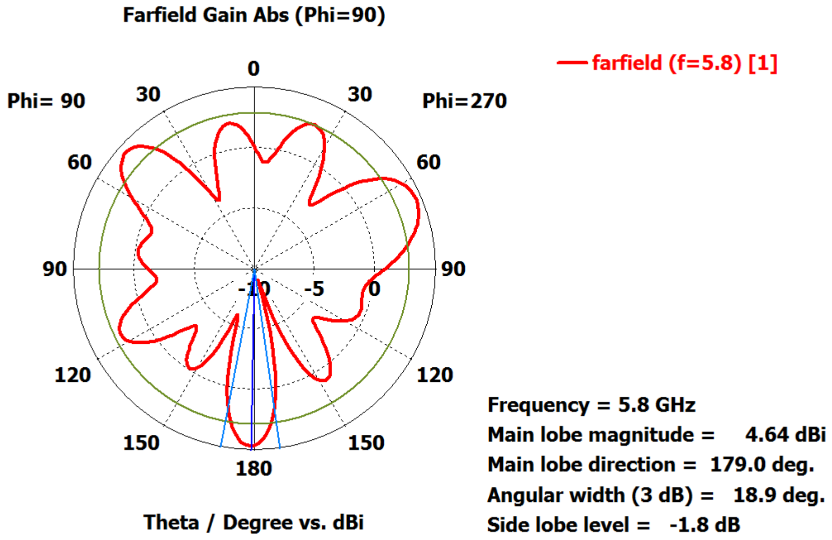

Fig. 4.11. **Radiation pattern of the single triangular patch antenna at 5.8 GHz**

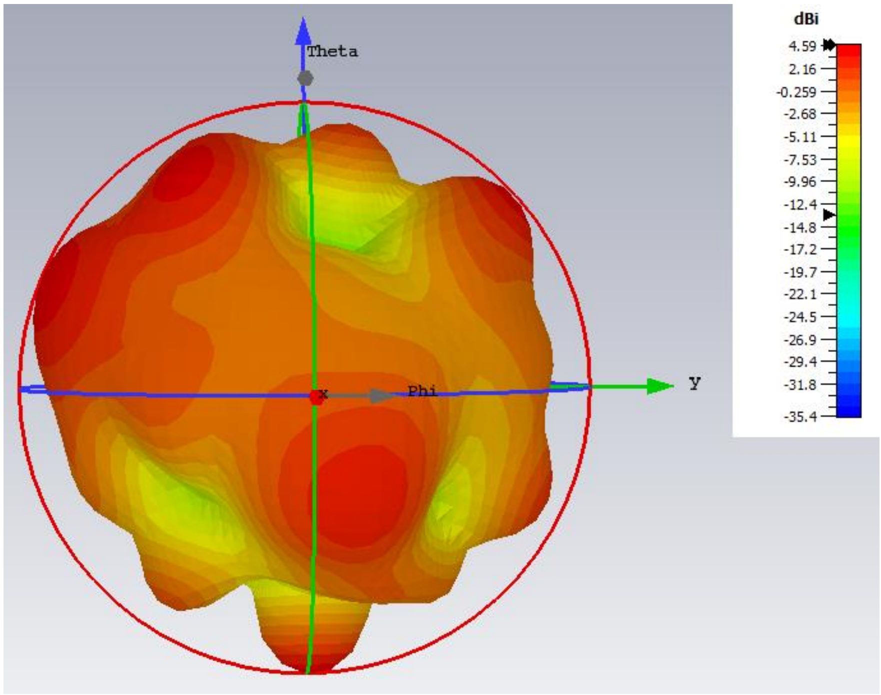

Fig. 4.12. **3D radiation pattern of the single triangular patch antenna at 5.8 GHz**

From Fig. 4.9 and Fig. 4.10, it can be seen that S11 is –24 dB at 5.78 GHz and –18 dB at 5.8 GHz. S21 is –4.5 dB which provides 35% power transfer efficiency for the single patch operating at 5.8 GHz. The radiation pattern in Fig. 4.11 shows the gain equaling

4.64 dB at 5.8 GHz for the single triangular patch. The 3D pattern is depicted in Fig. 4.12.

4.4. Array Results at 5.8 GHz

The array results are obtained for the 5.8 GHz frequency band. The reflection and transmission coefficient are displayed in Fig. 4.13 and Fig. 4.14, respectively. S11 is –26 dB which shows a good impedance matching in the system. The polar and 3D radiation pattern are depicted in Fig. 4.15 and Fig. 4.16, respectively. As seen, S21 is –3.6 dB which accounts for 44% of power transfer efficiency. Compared to the 2.4 GHz array which improved the power transfer of single patch by 45%, the power transfer efficiency at 5.8 GHz is only improved by 11%. It implies that a more efficient design might be needed for higher frequency band.

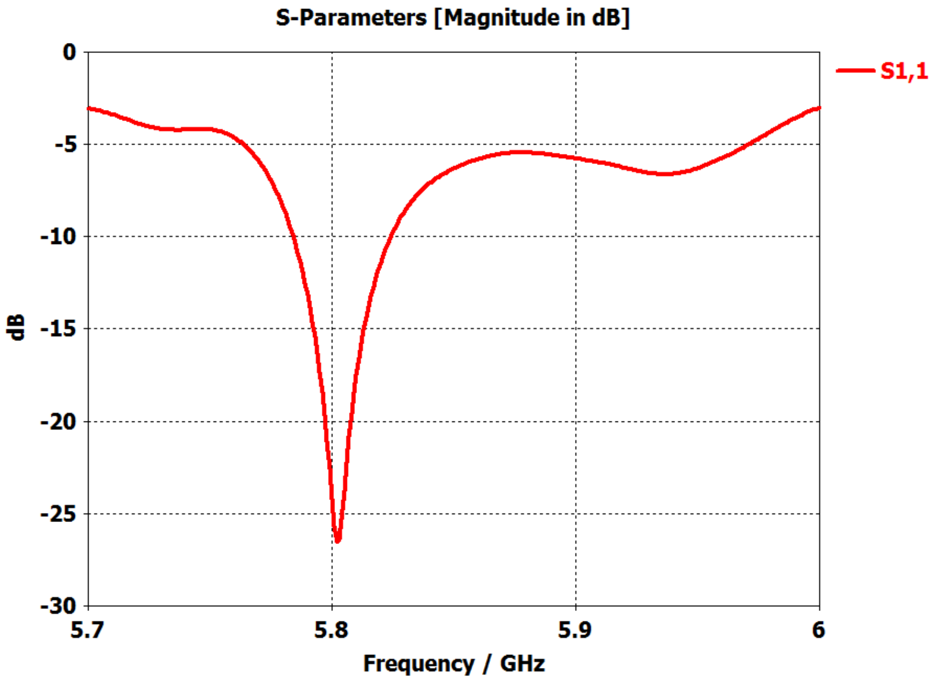

Fig. 4.13. **S11 parameter of array antenna system at 5.8 GHz**

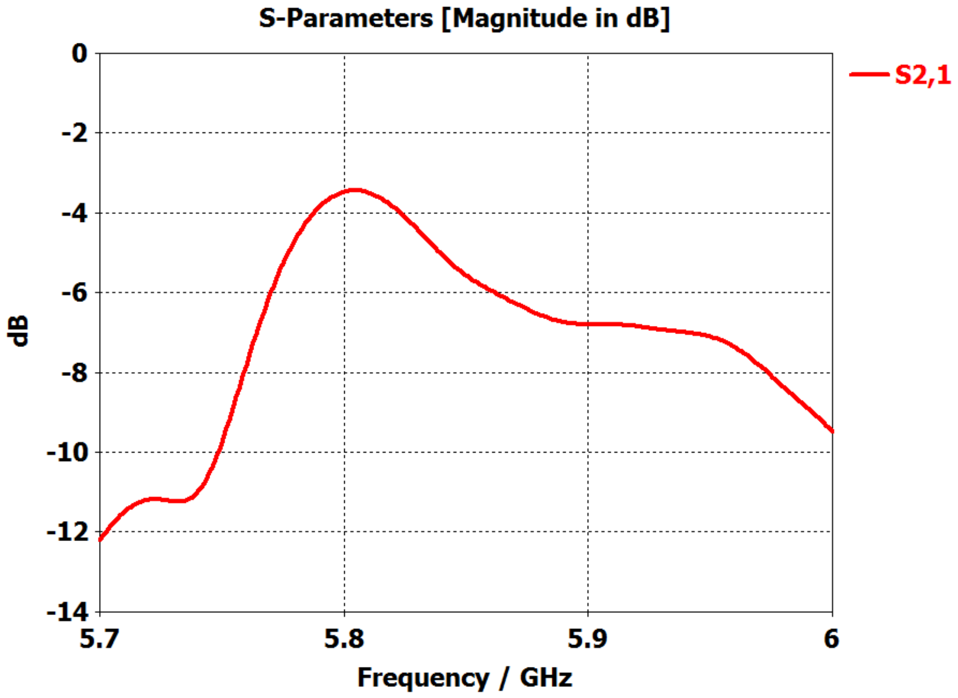

Fig. 4.14. **S21 parameter of array antenna system at 5.8 GHz**

As seen in Fig. 4.15, the array gain is less than the gain at 2.4 GHz which can be due to Ohmic losses at higher frequencies. At higher frequencies, due to the skin effect, the whole metal patch might not be used to radiate. This can lead to more Ohmic losses and decrease the gain.

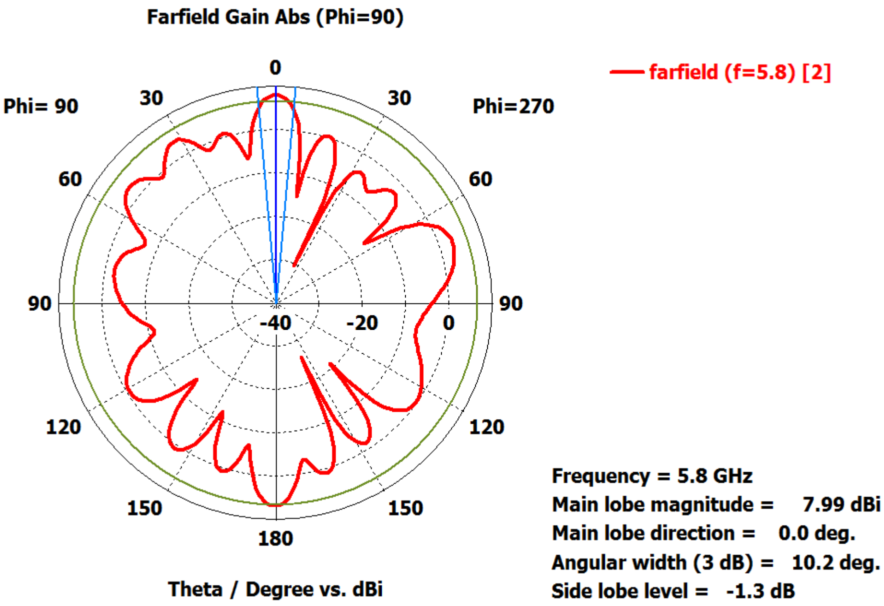

Fig. 4.15. **Radiation pattern of array antenna system at 5.8 GHz**

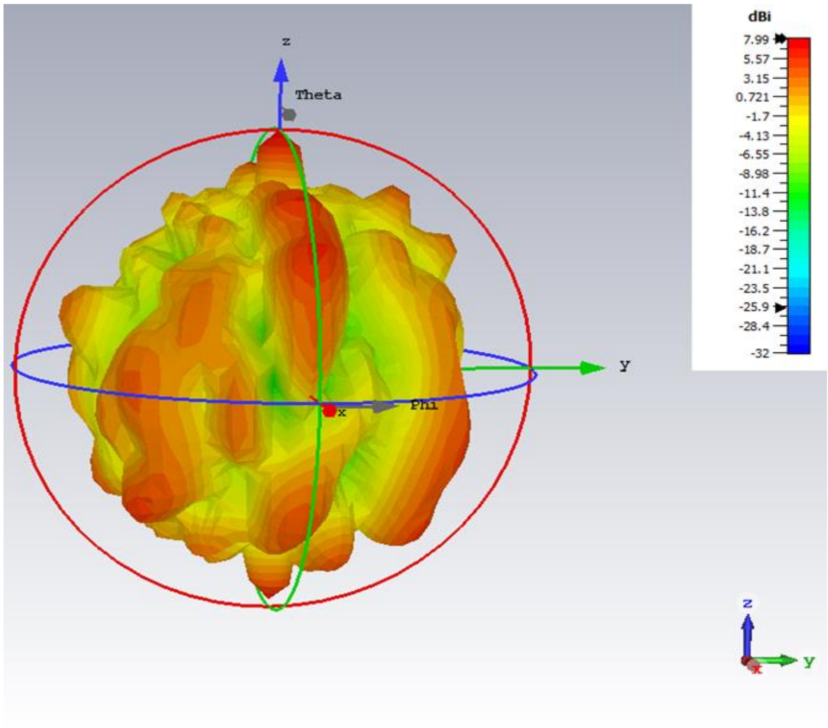

Fig. 4.16. **3D radiation pattern of the proposed array at 5.8 GHz**

4.5. Tilted Array Results at 2.4 GHz

The reflection coefficient, S11, is –33 dB at 2.39 GHz and -24 dB at 2.4 GHz which proves a proper impedance matching is met and is shown in Fig. 4.17. S21 is –0.55 dB which means an efficiency of 88%. Figure 4.19 shows the radiation pattern. The gain is 14 dB which is the highest at 2.35 GHz. The far-field gain is more useful when working in a farther distance. The HPBW is 25.1 which is more than HPBW in [4]. In comparison with [4], the number of elements are less and the Half-Power Beam-width is higher.

The tilted triangular antenna is designed for an improved HPBW and it is shown that the efficiency is comparable to the previous works while enjoying less number of elements. The elements are rotated 45^{o} off-axis and the performance is investigated. The simulation is conducted using CST Microwave software. The far-field results are also shown to better account for the performance in case the transmitter and receiver move farther from each other, unexpectedly. The results show 88% efficiency and 25.1^{o} HPBW.

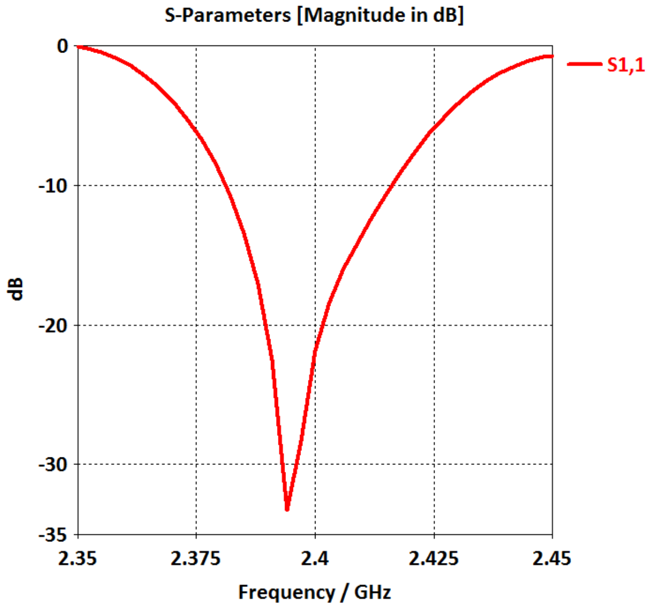

Fig. 4.17. **S11 parameter of tilted triangular array at 2.4 GHz**

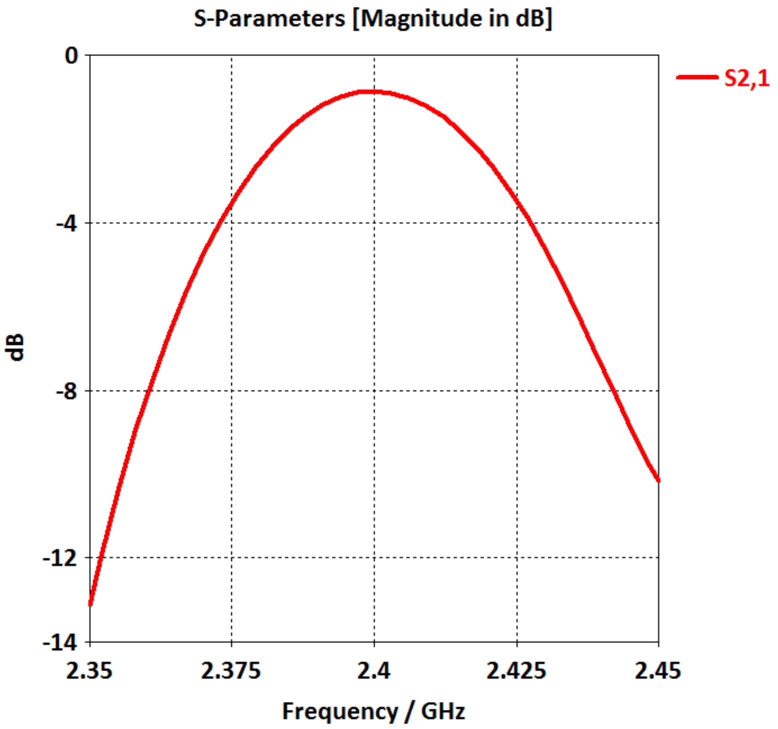

Fig. 4.18. **S21 parameter of tilted triangular array at 2.4 GHz**

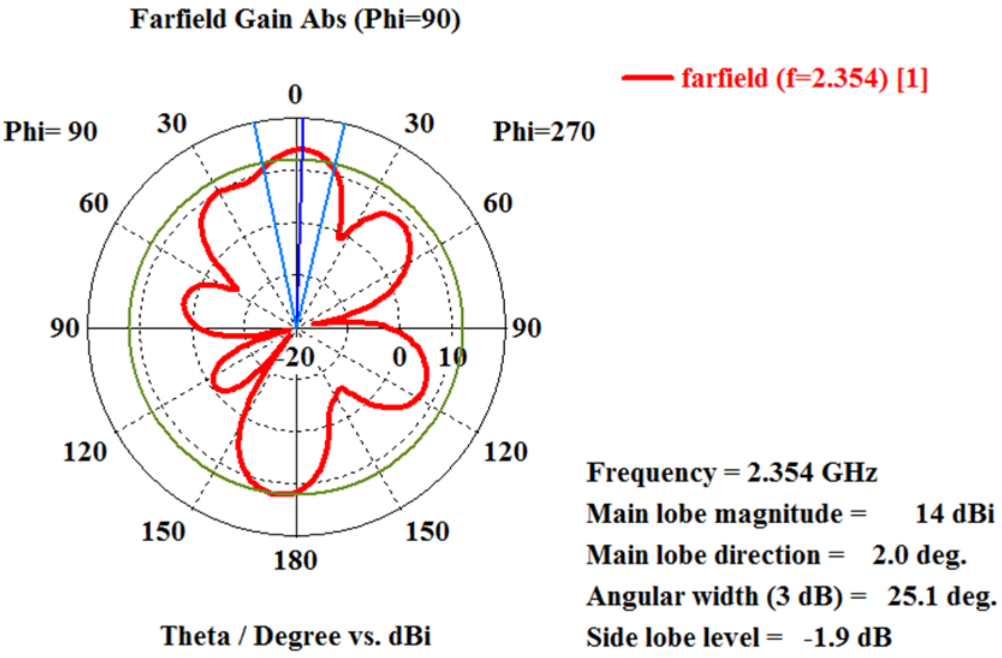

Fig. 4.19. **Radiation pattern of array antenna system at 5.8 GHz**

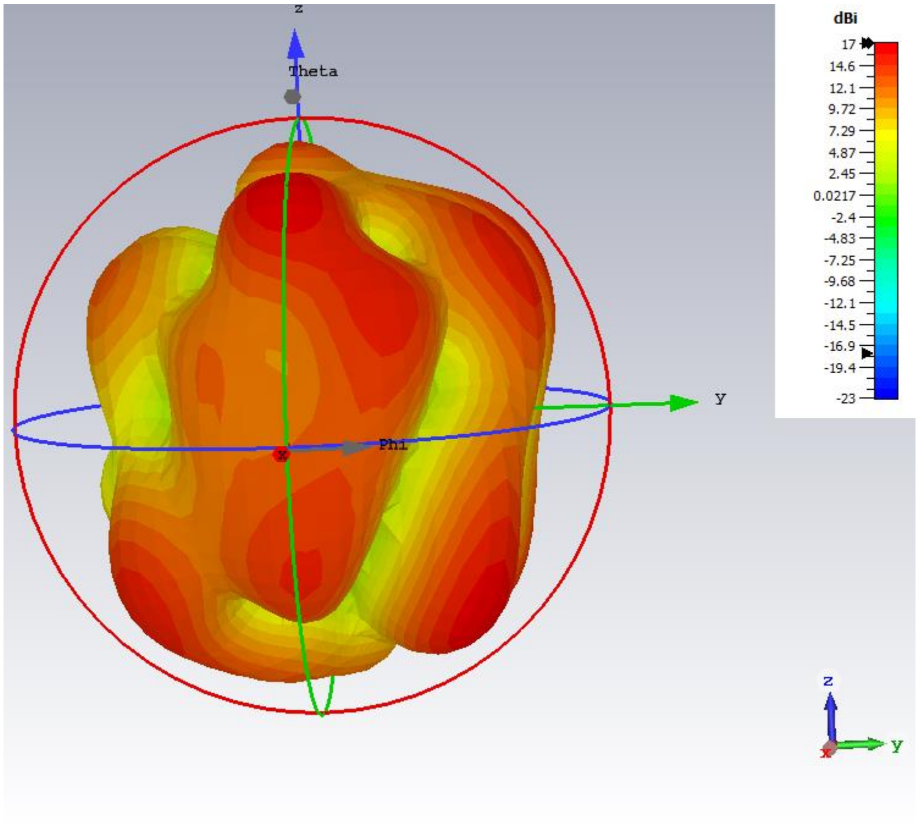

Fig. 4.20. **3D radiation pattern of the proposed array at 5.8 GHz**

The structure in [4] is depicted in Fig. 4.21 which is an 8×8 or 64-element array of rectangular elements. Table 4.1 compares the results reported in [4] and our results. The far-field results are provided due to the fact that if the distance increases for any reason, there is a sufficient amount of power transferred if there are satisfactory far-field results. The efficiency for [4] is 88% which is achieved using 64 elements. In the current thesis, a power transfer rate of 89% is obtained using only 4 elements. The gain is roughly the same in both works, though the current work provides a better HPBW and higher efficiency.

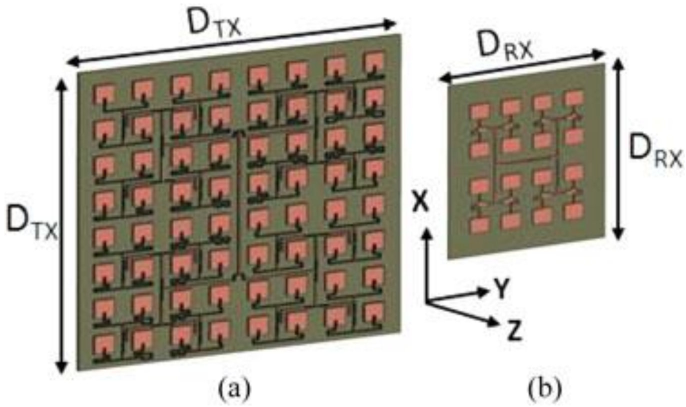

Fig. 4.21. **Patch array antennas. (a) 8 × 8 Tx array. (b) 4 × 4 Rx array (D_{TX} = 21.7 cm, D_{RX} = 16 cm) [4].**

Table 4.1: **Comparison to Other Configurations**

Reference	***Array elements***	***Efficiency***	***HPBW (deg)***	***Gain (dB)***
Proposed Array	2×2	89%	23.5 deg	17.7
Tilted Array	2×2	88%	25.1 deg	14
[4]	8×8	88%	20.7 deg	17.7
[35]	16	30%	NA	NA

4.6. Conclusion

The results show that using the triangular array, better efficiency is obtained compared to the single patch antennas. Moreover, a better efficiency is acquired compared to [4] and [35] although less elements are used. As seen earlier in this chapter, the proposed structure has improved results in 2.4 GHz frequency band. The improvement is less in 5.8 GHz frequency band which makes the structure more suitable for the 2.4 GHz frequency band. The tilted array shows good results and 88% efficiency.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The results obtained from simulation have shown that triangular array provided better efficiency compared to the single patch antennas. An improved efficiency compared to [4] and [35] is reported while less numbers of elements were used.

5.1. Conclusion

WPT has changed our inception of carrying power. It has not been a long time since the idea of transferring energy through air crossed a human being's mind, and it was not until recently that researchers started to look seriously into that. The recent works focused on the method of transferring power considering many elements such as efficiency, the amount of power transferred, safety, etc. The motivation behind this thesis was to increase the efficiency of the power transfer compared to the previous works. We have selected microstrip antennas since they enjoy a lightweight and low-profile structure. In this thesis, we have shown that microstrip antennas can be utilized efficiently to carry power wirelessly. One of the main features in deciding whether a WPT system is proper is efficiency. We have demonstrated that using an array of triangular patch antennas can improve the efficiency of the system. Moreover, this goal is accomplished by an array which has less elements compared to similar works done before. Both transmit and receive arrays are identical to make sure they have the maximum mutual coverage. The microstrip antenna is selected since it is compact, lightweight and low-profile. Also, it is conformal meaning it can be mounted on any type of device whether planar, cylindrical or any other shape.

The approach that has been used is classified as a type of Near-field method. The design can be used in different applications. A couple of them mentioned as follows:

- This design can be used to transfer power and charge batteries for example in EVs. This type of WPT is most useful in charge stations such as highway EV charge station.

- Moreover, it can be used in biomedical implants such as stunts, defibrillator, and many other life-saving devices.

In this thesis, the novel feature that is used includes using triangular microstrip patches in a 2×2 array. The desired outcome was met which is increasing the efficiency of the power transmission. The structure is compact, but at the same time it provides high efficiency and proper gain to optimize the power transfer.

5.2. Future Work

There exist some aspects in WPT yet to be improved. One can question the amount of power involved. Since there are other standards of deciding the efficiency of the WPT in a system, there can be investigations on the total amount of input and output power, and other factors. Trying to achieve better results, other shapes of microstrip antennas can be investigated. They can be used in simple shapes or fractals. The substrate considered can be a metamaterial one or meandered and defected grounded as well as Epsilon-Near-Zero (ENZ) materials. Size reduction of such systems can also be considered to perform especially in biomedical and implanted devices. Other works can include designing a solar powered small battery charger for a pacemaker or any other biomedical device. One of the drawbacks of WPT is difficulty maintaining constant load impedance due to blockage or changes in the distance. A possible future work might include providing a steady power supply to biomedical sensors using methods such as MEMS switches, and etc.

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