Design a Prototype of Wireless Power Transmission System Using RF/Microwave and Performance Analysis of Implementation

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***Abstract*—A prototype of wireless power transmission (WPT) system has been designed in small scale which can be used to drive portable electronic devices. For power transmitting purpose RF/microwave has been used. A detail discussion on transmitting and receiving antenna of WPT system has been presented. The step by step design method has been used in designing the entire system. Then, a simple practical approach has been demonstrated. The detail performance on the practical implementation of wireless power transmission system has been analyzed. The 4GHz designed system provides 2W receiving power when the transmitter sends 20W from a distance of 52m. The difficulties and limitations for implementing the designed model in the laboratory have been featured. Then, the ideas for overcoming the limitations also have been proposed.**

***Index Terms*—Power transmission, wireless, microwave, load, antenna, amplifier, rectifier.**

I. Introduction

Wireless energy transfer or wireless power transmission (WPT) is the process that takes place in any system where electrical energy is transmitted from a power source to an electrical load without the use of wire. Wireless transmission is ideal in cases where instantaneous or continuous energy transfer is needed. The potential applications of wireless power transfer include charging of mobile phones and laptops [1], radio-frequency identification (RFID) [2], electrically charged vehicles [3], biomedical sensors [4], space solar power satellite (SPS) [5], solar energy to earth, and in spying circuits devices which if contain a power source can have greater probability of detection etc.

The various methods of wireless power transfer are:

- Microwave/ Radio wave [6].
- Plastic sheet [7].
- Inductive coupling [8].
- Lasers [9].

Among these methods of wireless power transfer, using microwave has some advantages over other methods such as its use for longer distances with relatively higher efficiency and more mature technology [10]. Highly efficient, super directive array configuration would have the potential of concentrated and directed microwave beam that can provide higher efficiency for longer distances.

The objective of this work is to design a power transmission system through wireless medium in small scale so that the power received from the receiver can be utilized to drive portable electronic devices which require very low power to operate. Practical difficulties to implement a prototype have also been analyzed.

This research paper is organized as follows. A brief description of transmitter parts of the WPT system and the required parameters to design transmitting antenna are presented in Section 2. Section 3 discusses the receiver parameters and parts of WPT system, while some important design parameters for different elements of WPT system are briefly described in Section 4. Section 5 highlights the practical implementation and experimental data of the system. The antenna performances have been analyzed in Section 6. The practical antenna's limitations and proposal to overcome the limitations have been discussed in Section 7. Finally, some concluding remarks have been highlighted in Section 8.

II. Transmitter of WPT System

The block diagram of a typical transmitter unit of WPT system is shown in Fig. 1. There is always a large amount of signal power loss in the free space while the microwave signal propagates through it. To compensate this loss at the receiver side, the transmitter of the wireless power transfer system should be capable of transmitting a high power. For this reason the transmitting antenna should have high performance.

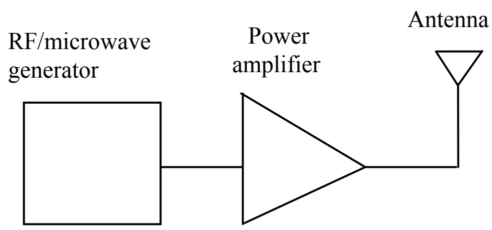

Fig. 1. The block diagram of transmitter unit of WPT system.

Various types of antennas are practically used. Some examples of the antennas are horn antenna, dish antenna, rhombic antenna, V-antenna, T-antenna etc. Before selecting which type of antenna should be used, the following points have to be considered:

1) The antenna is capable of operating in the RF/microwave range.

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2) The antenna has high directivity and gain.
3) The antenna is highly directional.

Taking above points into consideration and for simplicity dish antenna is selected as the transmitting antenna for the designing purpose of WPT system. A typical parabolic antenna consists of a parabolic reflector illuminated by a small Feed as shown in Fig. 2. The reflector is a metallic surface formed into a paraboloid of revolution and (usually) truncated in a circular rim that forms the diameter of the antenna. This paraboloid possesses a distinct focal point by virtue of having the reflective property of parabolas in that a point light source at this focus produces a parallel light beam aligned with the axis of revolution [11].

Fig. 2. Parabolic dish antenna.

III. Receiver of WPT System

The receiver of the wireless power transmission system is one of the most essential part. The wireless power output is taken from the receiver unit; hence the performance of receiver antenna is much significant. As the main purpose of our receiver unit is to charge-up a rechargeable battery, its receiver unit should have the following properties:

1) It must be capable of collecting enough power from the transmitted power wirelessly.
2) It should detect the power wave with correct frequency band.
3) It should be capable of giving dc output though the received power is ac.

Keeping these points into consideration the schematic diagram of the receiving unit is shown in Fig. 3. From the diagram it can be said that, the receiver antenna is nothing but a Rectenna.

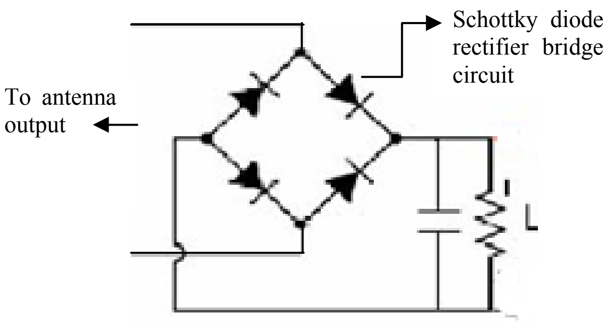

Fig. 3. Schematic diagram of receiver unit.

A Rectenna is a rectifying antenna, which is used to convert microwave energy into DC electricity. Its elements are usually arranged in a multi element phased array with a mesh pattern reflector element to make it directional [12].

A simple rectenna can be constructed from a Schottky diode placed between antenna dipoles. The diode rectifies the current induced in the antenna by the microwaves. Schottky diodes are used because they have the lowest voltage drop and highest speed and therefore waste the least amount of power due to conduction and switching. Rectennas are highly efficient at converting microwave energy to electricity. In laboratory environments, efficiencies above 85% [12] have been observed with regularity. Some experimentation have been done with inverse rectennas, converting electricity into microwave energy, but efficiencies are much lower-only in the area of 1% [13]. Due to the high efficiency and relative cheapness of rectennas, they feature in most microwave power transmission proposals. As the receiving unit will be used in the portable system so the receiving antenna should be small. At the same time this receiving antenna should has very high gain. From the study and analysis it has been found that, microstrip patch antenna supports these properties.

IV. Design of the WPT System

In this section a complete wireless low power transfer system has been designed from the analysis discussed in the previous sections. The purpose of this design scheme is to drive portable electronic devices which utilize low power. For this incentive some values of designing advantage will first be assumed.

In Fig. 4 a detailed system for wireless power transfer has been shown.

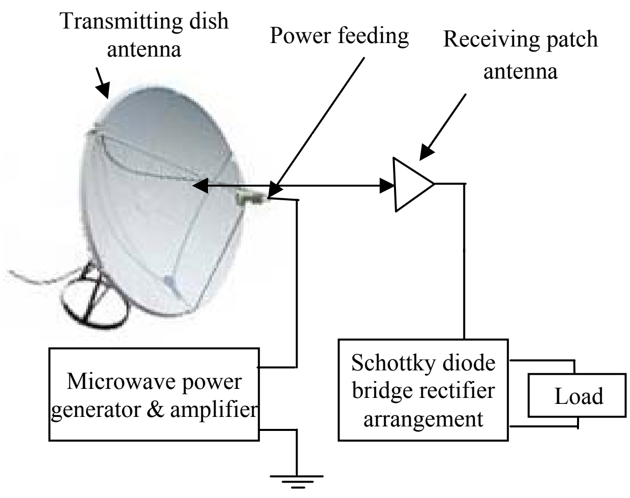

Fig. 4. Complete wireless power transferring system.

A. Load Assumption

To receive low power from the system a rechargeable battery is considered as the load. The specification of a typical mobile battery is as follows:

Input volt: 3.7 V
Input current: 350 mA

So the input DC power required will be, P_{dc} =1.295 W ≈ 1.3 W.

B. Designing the Schottky Diode Rectifier Output and Input Power

It has been estimated that the diode bridge rectifier arrangement should have output power of 1.3 W. This power pure DC. But the input power to the rectifier should be sinusoidal AC. The DC power obtained from a sinusoidal signal is equal to the average power of that signal. If P_{ac} and P_{dc} are the sinusoidal AC power and DC power respectively then, $P_{ac} = P_{dc} \times \frac{\pi}{2}$. Therefore, the input AC power to the full-wave rectifier bridge arrangement is, P_{ac} = $1.3\times \frac{\pi}{2}$ = 2.04 ≈ 2 W.

C. Designing of the Microstrip Patch Antenna

A patch antenna has been designed using the patch antenna simulation software Zeland IE3D [14]. Some values are required to give in the software input. The following values were assumed as:

1) The operating frequency, f_r = 4 GHz
2) Substrate dielectric constant, ε_r = 2.5
3) Height of the patch, h= 0.787 mm

The width of the patch [15] is calculated as,

$$W = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} = 28.3277 \text{ mm}$$

And the effective dielectric constant [15] is estimated as,

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} = 2.3995$$

The extended dimensions of the patch along its length ΔL is estimated as [15],

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{w}{h}+0.8)} = 0.408 \text{ mm}$$

Now, the length of the patch [15],

$$L = \frac{1}{2\,f_r\sqrt{\epsilon_{reff}}}\frac{1}{\sqrt{\mu_0\epsilon_0}} - 2\,\Delta L = 23.3759 \text{ mm}$$

Putting these values in the software input the designed antenna was established. Results found using software simulation is shown in Table I. The effective aperture of the designed patch antenna is calculated as, A_{er} = *22.15 × 28.25–9.975×14.25=483.59≈485 mm²*. The schematic of designed patch is presented in Fig. 5.

TABLE I: PROPERTIES OF ANTENNA

Sl. no.	Property	Value
1	Antenna frequency	4 GHz
2	Incident power	0.01 W
3	Input power	0.00999961 W
4	Radiated power	0.00815789 W
5	Antenna efficiency	81.582 %
6	Gain	6.62428 dBi
7	Directivity	7.50851 dBi
8	Optimized length of the patch (L)	22.15 mm
9	Optimized width of the patch (W)	28.25 mm
10	Optimized length of the inset feed	9.975 mm
11	Optimized width of the inset feed	14.25 mm

D. Designing Patch Antenna Arrays

From the output of patch antenna design shown in the Table I the radiated power of patch antenna is found to be 0.0081579 W which is very less in comparison with the load. To increase this power, arrays of patch antenna have to be used. In corporate-feed network the power splits of 2^n (n= 2, 4, 8, etc.). So in reverse order if we use arrays of n patches then the total power output will multiplied by 2^n.

Total output power, P_{to} = 2 W. But, the output power from individual patch, P_o = 0.00815789 W. Therefore, power multiplication factor, P_{to}/P_o = 245.16. Now, 2^n = 245 and n = 7.936 ≈ 8. Thus, the number of patches in the array is 8.

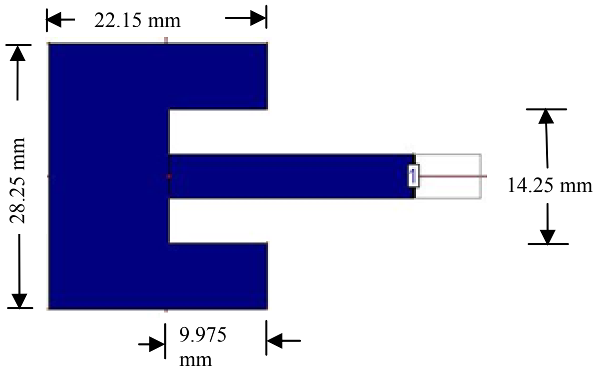

Fig. 5. Dimension of the designed patch.

In Fig. 6, the connections of arrays of 8 patches are presented to get our required output power. This is the final designed view of the receiving antenna. Thus, the total aperture of the receiving antenna, $A = 485 \times 10^{-6} \times 8 \text{ m}^2 = 3.88\times10^{-3} \text{ m}^2$.

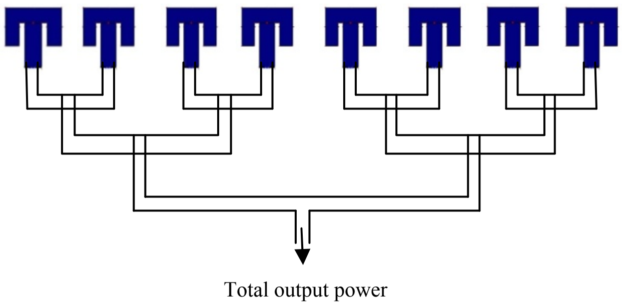

Fig. 6. Arrays of eight patches to get required output power.

E. Designing of the Dish Antenna

Power loss in the environment is to be 18.5 W. Consequently, the transmitting power, P_t= 20 W.

From the Friis transmission formula the effective aperture, A_{et} of the dish antenna is established. Friis transmission formula is, $\frac{P_r}{P_t} = \frac{A_{er}\,A_{et}}{r^2\,\lambda^2}$, Therefore, $r = (\sqrt{\pi P_t A_{er}/_{P_r\lambda^2}})d$. Putting all the values we find the relation between *r* and *d* as, *r = 4.655d*. Again, using different values of dish diameter different separations is found which have been shown in the Table II.

TABLE II: SEPARATION BETWEEN TWO ANTENNAS AT DIFFERENT TRANSMITTING ANTENNA'S DIAMETER

Sl. no.	Transmitting antenna's diameter (m)	Separation between two antennas (m)
1	10	46.55
2	12	55.86
3	18	83.79
4	22	102.41

Taking separation between the transmitter and the receiver to be 56 m and diameter of the dish is 12 m. The directivity of the dish antenna, $D = 9.87\left(\frac{d}{\lambda^2}\right) = 21056$. Thus, $D_{dB} = 10 \log_{10} 21056 = 43.23$ dB. The gain, $G = 6\left(\frac{d}{\lambda^2}\right) = 12800$ and $G_{dB} = 10 \log_{10} 12800 = 41.07$ dB. From the design details, the specification of the microwave power generator comprising with power amplifier is given as maximum output power = 4 W and maximum output frequency = 4.5 GHz. Total design overview is shown in Table III.

TABLE III: TOTAL DESIGN OVERVIEW OF WPT SYSTEM

Load		Patch arrays	
Load power	1.3 W, DC	No of patches	8
Schottky diode rectifier		Total receiving antenna aperture	3.88×10^{-3} m^2
Input power	2W, AC	Dish antenna dimension	
Input voltage	4.5 V, AC	Dish diameter	12 m
Operating frequency	4 GHz	Dish effective area	452.4 m^2
Microstrip patch antenna dimension		Dish antenna properties	
Patch length	22.15 mm	Antenna frequency	4 GHz
Patch width	28.25 mm	Radiated power	3.5 W
Length of inset feed	9.975 mm	Gain	43.23 dB
Width of inset feed	14.25 mm	Directivity	41.07 dB
Antenna effective aperture	485 mm^2	Microwave generator	
Microstrip patch antenna properties		Maximum output power	4 W
Antenna frequency	4 GHz	Maximum output frequency	4.5 GHz
Radiated power	0.008158 W	Others	
Antenna efficiency	81.582 %	Distance between antennas	52 m
Gain	6.6243 dBi		
Directivity	7.5085 dBi		

V. PRACTICAL IMPLEMENTATION AND EXPERIMENTAL DATA

The focus of this challenge was to design and implement a prototype of battery charging system; so that a rechargeable battery could be charged up without connecting it with a general power supply system. To achieve this target, wireless power transmission system was the main concern. In the following sub-sections the ideas for implementing a wireless battery charging system have been discussed.

The aluminum wires that were used to implement antennas are used as the cable in the overhead power transmission line. The wires were cut into small parts of different lengths and those parts were rounded. Finally, the rounded wires were placed and attached on a wooden frame stand and the antenna was made. The diameter of each antenna is about 91 cm. For the experiment, same dimension antennas were used on both transmitting and receiving side as shown in Fig. 7.

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Fig. 7. Practical antennas after completion.

VI. ANTENNA PERFORMANCE

To justify the antenna performance properly, receiving signal frequencies and their corresponding amplitude at different transmitting frequencies were used. Table IV and Table V presents different performance parameters for distance between the transmitting and receiving antenna as 155cm and 280cm respectively. The antenna performances achieved from the Table IV and Table V are shown in Fig. 8 to Fig. 11.

From Fig. 8 and Fig. 9 receiving frequencies at different transmitting frequencies are shown. It is observed that the receiving frequencies are not same as the transmitting frequencies. Moreover, the difference between transmitting and receiving frequency at the same transmitting frequency increases if the distance between transmitter and receiver is increased. In the Fig. 10 and Fig. 11 the different receiving signal voltages at different transmitting frequencies have been plotted. It is found that receiving signal voltages varies between 2.5 to 4.5 mV. Also, the receiving signal voltage for the same transmitting voltage decreases if distance between transmitter and receiver is increased.

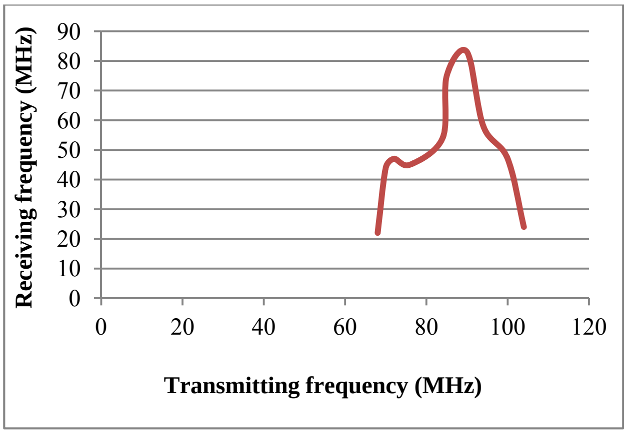

Fig. 8. Receiving frequency versus transmitting frequency when the distance between the antennas is 155 cm.

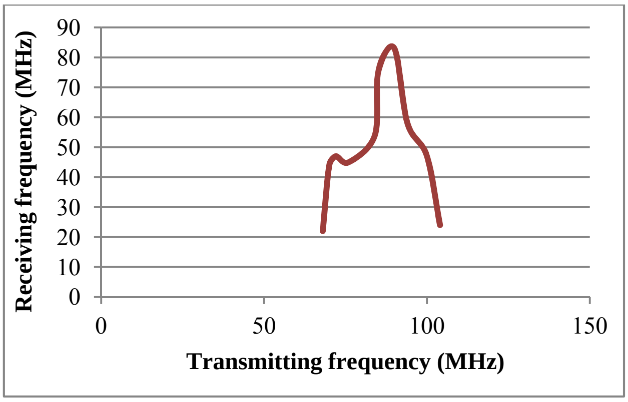

Fig. 9. Receiving frequency versus transmitting frequency when the distance between the antenns is 280 cm.

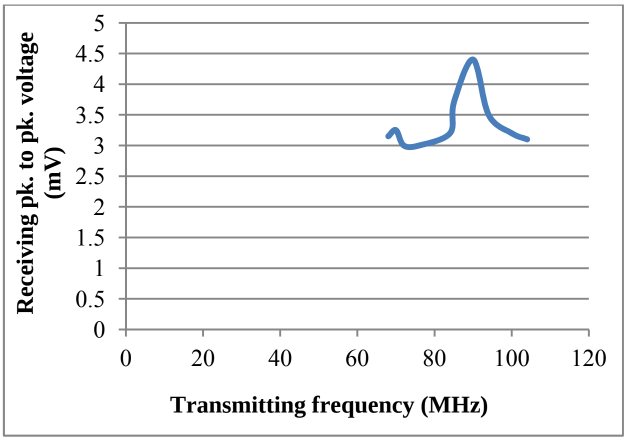

Fig. 10. Receiving voltage amplitude versus transmitting frequency when the distance between the antennas is 155 cm.

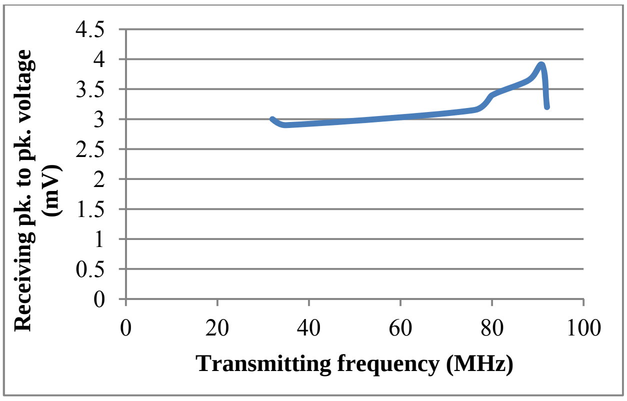

Fig. 11. Receiving voltage amplitude versus transmitting frequency when the distance between the antenna is 280 cm.

TABLE V: COMPARISON OF TRANSMITTING AND RECEIVING SIGNAL AT 280 CM DISTANCE BETWEEN THE TRANSMITTING AND RECEIVING ANTENNA

Transmitting Frequency (MHz)	Receiving frequency (MHz)	Receiving peak to peak voltage (mV)	Remarks on signal quality
32	10.5	3.00	good
35	11	2.9	good
76	13	3.15	good
80	27	3.4	better
88	62	3.65	very good
91	61	3.9	very good
92	20	3.2	poor

TABLE IV: COMPARISON OF TRANSMITTING AND RECEIVING SIGNAL AT 155 CM DISTANCE BETWEEN THE TRANSMITTING AND RECEIVING ANTENNA

Transmitting Frequency (MHz)	Receiving frequency (MHz)	Receiving peak to peak voltage (mV)	Remarks on signal quality
68	22	3.15	good
70	44	3.25	better
72	47	3.00	better
76	45	3.00	better
84	54	3.2	very good
85	75	3.7	very good
90	83	4.4	very good
94	58	3.5	better
100	47	3.2	good
104	24	3.1	poor

VII. LIMITATIONS AND REMEDY

From the experimental analysis the following limitations of implementation were found:

1) The antenna performance was limited to small distance.
2) There were some noises and signal distortions in receiving antenna. The noise increases with the increase of distance.
3) There was always a frequency mismatch between transmitting and receiving signal.
4) The frequency of the received signal varies with time at a very large frequency band.

The main component of the receiver circuit is the Schottky diode. Schottky diode capable of operating in the frequency range of 80 to 100 MHz was required, as the antennas operate better in these ranges. But unfortunately, the Schottky diodes available in Bangladesh have operating frequency greater than this range. The experiments were done by using available Schottky diodes. The maximum frequency of the RF transmitter in the laboratory was 150 MHz, but the designed device required GHz frequency range to work. To increase the transmitter frequency a number of transmitters are needed to cascade one after another.

VIII. CONCLUSION

This research work was aimed at designing a prototype of wireless power transmission system. Detailed analysis of all the system components has been discussed. For design purpose the system was divided into two parts i) transmitter and ii) receiver. In transmitter side, the transmitting antenna was designed. For simplicity, greater directivity, and large power handling purpose dish antenna was used as the transmitting antenna. In receiving side microstrip patch antenna was used as it is a low profile antenna. The output power from a single patch antenna is less. Consequently, arrays of patches were required to obtain required power. The designed system's operating frequency is 4 GHz, gives output power of 2W at receiving end using input power of 20 W at transmitting end while distance between transmitter and receiver is 56 m. The distance can be increased if the operating frequency is increased.

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