Characterization of Wireless Power Charging Receiver for Mobile Device

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Abstract: In this paper, the characterization of wireless power charging receiver for mobile device developed based on magnetic resonance coupling is presented. The receiver is constructed of an electromagnetic waves radiator which is implemented by use of microstrip patch on a dielectric substrate to operate at frequency of around 10MHz and a rectifier circuit which comprises of a voltage doubler circuit. Prior the hardware realization, the designed of receiver is performed through simulation to investigate the influence of level and frequency of input voltage to the DC voltage of rectifier circuit output. The radiator efficiency and performance of rectifier circuit are two things that are focused in the investigation. From the experimental characterization, it shows that the radiator efficiency for a considerable gap is more than 37% for some level of varied input AC signal. While the DC voltage of rectifier circuit output has the voltage deviation less than 2% for operating frequency of input voltage varied up to 20%. In addition, it is demonstrated that the receiver is able to start charging a battery of mobile phone by producing 4.12V_{DC} at the output of receiver with the gap separation between 2 radiators of 0.8mm.

Keywords: Mobile device, radiator, receiver; rectifier circuit; voltage doubler; wireless power charging.

1. Introduction

Wireless power transfer is basically a mechanism whereby electrical energy can be transmitted from a power source to the electrical target load without cable. The technology of wireless power transfer has been becoming a very attractive research especially for wireless charging application due to the necessity of more convenient method in charging a mobile device. Several methods to transfer electrical power wirelessly by using laser technology and frequency radiation on radiowaves have been investigated and developed experimentally [1]-[4]. Even some method has also been implemented and going around into market. Unluckily, several technical limitations have made the method to be unsuitable for the system. A method known as power beaming has been implemented by radiating electromagnetic beams in far-field region such as microwave or laser beams [1]–[2]. This method is categorized as a radiative method where it can transmit high electrical energy in longer distances. However, an important issue that should be paid more attention in wireless power transfer system is a limitation of power exposure. This aims to avoid the exposure to people or other living things of potentially harmful electromagnetic radiation. Other method which is classified as non-radiative technique is usually applied to transfer wirelessly the electrical energy for low power device in near-field region [3]–[4]. Due to the received power weakness on receiver circuit, however the power in the receiver circuit that applies this method should be strengthened using some external power source.

Apart from the methods mentioned above, another method using near-field approach available for wireless power charging system is implemented based on the magnetic resonance coupling. In last 5 years, this method has been widely implemented in many wireless power

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transfer applications [5]-[12]. An important issue that should be paid more attention in wireless power transfer application is the efficiency. The issue is mainly determined by devices applied for transferring energy of electromagnetic waves. In [11], the use of microstrip patch deployed on dielectric substrate is one of promising technique which can be implemented for achieving better efficiency for desired operating frequency. Furthermore, the external power source in some wireless power charging is still becoming a required thing to be included in the system. The rectifier circuit which is usually implemented for receiver of wireless power transfer system is commonly supplied by power source. Hence, in [12]-[13], the configuration of voltage doubler has been proposed to overcome the problem as well as to simplify the circuit design. Theoretically, the voltage produced by a voltage doubler circuit is twice of the peak of AC input voltage. However, the use of diodes as main components the circuit also faces with the problem of the voltage drop of the diodes which leads to the power loss of the circuit [8], [14]. Hence, this can be overcome by implementing the diodes with low voltage drop such as germanium diode.

In this paper, the development of wireless power charging receiver for mobile device is constructed using the radiator as a device for transferring electrical energy and the voltage doubler as a rectifier circuit. The radiator is implemented using a microstrip patch on an FR4 Epoxy dielectric substrate, while the receiver circuit comprises of rectifier circuit configured with a voltage doubler is driven by germanium diode of 1N4149 types. Some brief description related to the concept of magnetic resonance coupling will be explained prior the design of receiver system. Then an overview of receiver circuit design and its related equations will be elaborated, followed by hardware realization and experimental characterization. Some discussion related to the results of characterization will be presented, and a conclusion will be pointed out at the end of paper.

2. Overview of Wireless Power Charging Receiver

A. Magnetic Resonance Coupling

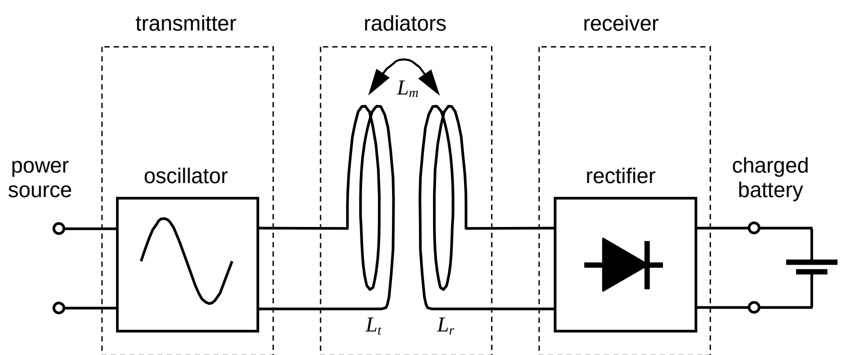

Figure 1. Block diagram of wireless power charging system

A block diagram of wireless power charging system based on magnetic resonance coupling is illustrated in Figure 1. It is consists of three parts; a transmitter to generate the AC signal to be transferred, transmitting and receiving radiators to transfer the power of AC signal wirelessly, and a receiver to convert the received AC signal into DC voltage for charging the battery of mobile device. Based on the concept of magnetic resonance coupling, the power of AC signal from the transmitter is transferred to the receiver through radiators based on magnetic coupling. The current change in the transmitting radiator which influences the magnetic field around it will induce the voltage in the receiving radiator. The mechanism of power transfer occurs due to the mutual coupling of magnetic field between 2 radiators. Whilst the efficiency of power transfer, it is determined by the value of coupling coefficient where the separation between 2 radiators is one of the essential factors. The coupling coefficient between

2 radiators is given by (1) where L_m is a mutual inductance representing the mutual magnetic coupling between 2 radiators, L_t and L_r are self inductance for transmitting radiator and receiving radiator, respectively. The main objective of the proposed system is to deliver electrical energy from a power source as much as possible to the load where in the implementation it is manifested as a battery of mobile device. Therefore, the efficiency of power transfer from the transmitting radiator at transmitter to the receiving radiator at receiver should be maximized to produce sufficiently DC power at the output of receiver circuit.

$$k = \frac{L_m}{\sqrt{L_t L_r}} \tag{1}$$

B. Wireless Power Charging Receiver

Figure 2 shows a circuitry system of wireless power charging receiver for mobile device. It comprises of a resonant circuit, i.e. receiving radiator, which is coupled magnetically with a transmitting radiator (not shown in the figure) and connected to the rectifier circuit to produce DC voltage to be supplied for the battery. The receiving radiator which is designed to operate around frequency of 10MHz is developed using an antenna-like structure of microstrip spiral patch as illustrated in Figure 3 [11]. The choice of spiral shape is aimed to significantly reduce the dimension of radiator, thence it can be realized in compact size. If the radiator is implemented in a straight line on an FR4 Epoxy dielectric substrate ($_r \approx 4.4$), the effective patch length (l_{eff}) which is calculable using (2) is around 7,151mm. This size is very long and inefficient to be applied for a palm-size mobile device. Therefore, by taking the spiral shape, the radiator dimension shrinks to merely 50mm x 60mm.

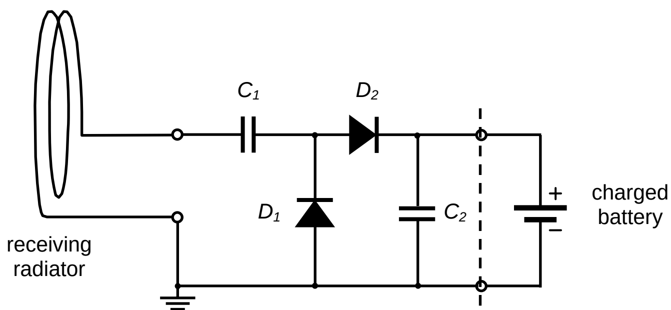

Figure 2. Circuitry system of wireless power charging receiver for mobile device

$$l_{eff} = \frac{c}{2 f \sqrt{\varepsilon_r}} \tag{2}$$

The received AC signal at receiving radiator is then converted into DC voltage using the rectifier circuit. As shown in Figure 2, the circuit is configured using a voltage doubler to obtain high enough DC voltage for charging the battery of mobile device. The working mechanism of voltage doubler is figured out as follows; by assuming the received AC signal at receiving radiator is a sinusoidal wave, when the AC signal has negative polarity, the diode D_1 is switched on and conducting the current from the ground to charge the capacitor C_1; in the next half period, when the AC signal source has positive polarity, the diode D_1 is then switched off; in contrary the diode D_2 is switched on and flowing the current from the AC signal to charge the capacitor C_2. Simultaneously, the capacitor C_1 discharges and conducts its charges to the capacitor C_2 through the diode D_2 affecting the capacitor C_2 to have double charges of capacitor C_1. In case components of rectifier circuit are ideal and lossless, then the voltage on the capacitor C_2 is almost twice of the peak voltage of AC signal. However, since components particularly the diodes are non-ideal, thence both diodes will lead to have the voltage drop, so the ideal condition assumption is no more valid. To obtain high enough DC voltage at the output of receiver, i.e. rectifier circuit, related to the voltage drop of diodes, one of the easiest methods is by employing diodes with low voltage drop such as germanium diodes instead of silicon diodes.

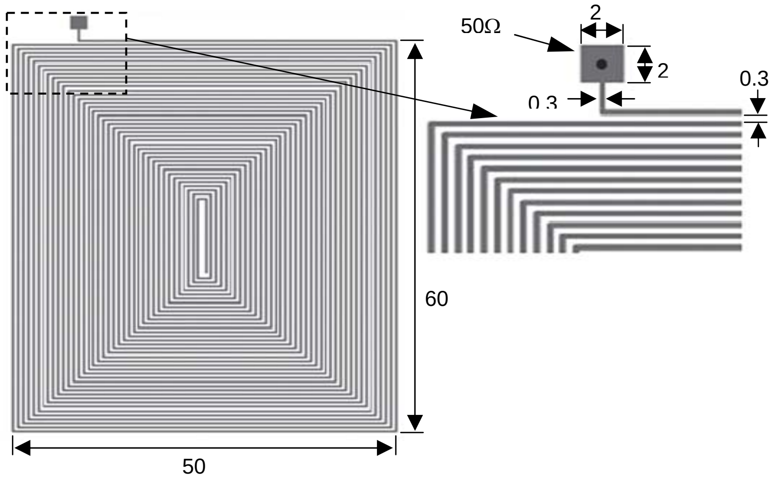

Figure 3. Receiving radiator for wireless power charging receiver and its geometry [11]

Furthermore, apart from the diode and its voltage drop, both capacitors C_1 and C_2 should be selected carefully. The lower the capacitance value of capacitor C_1, the more input reactance will be obtained leading to the impedance mismatch. Meanwhile, since the capacitance value of capacitor C_2 is related to the ability of storage charges, then the higher capacitance value means more charges can be stored which will produce a flat or ripple-free of DC voltage at the output of receiver. However, too large capacitance value affects the longer charging time of capacitor. From parametrical studies through the simulation, it is considered to use the capacitance value of 100nF for both capacitors.

3. Experimental Characterization and Discussion

A. Measurement of Radiator Efficiency

The scattering parameter of realized radiator, i.e. reflection and transmission coefficients, in which the gap separation between 2 radiators is set in to be 0.4mm, 0.8mm and 1.2mm is obtained from [11] and it yields a graph in Figure 4. It is noticeable that the realized radiator is suitable to be utilized at frequency range of 8-10MHz. The measured results show that the gap separation of 0.8mm produces stronger coupling compared than of 1.2mm.

In order to determine the efficiency of radiator, a various AC signal level obtained from a signal generator is fed to the transmitting radiator, while the received AC signal at the receiving radiator is measured in which the results are plotted in Figure 5 for gap separation between 2 radiators of 0.4mm, 0.8mm and 1.2mm. In this work, the radiator efficiency is defined as the ratio between the output and the input AC signal for some gap separation between 2 radiators. The measured radiator efficiency with gap separation of 0.4mm, 0.8mm and 1.2mm for 10MHz operating frequency is depicted in Figure 6. It seems that the radiator efficiency is inline with the measured scattering parameter where the radiator with gap separation of 0.8mm yields higher efficiency than of 1.2mm. The measured results shown in Figure 5 comply with the theoretical prediction as the larger the gap separation, the more severe the propagation loss will be. It can be concluded that the efficiency of radiator for the worst case of gap separation, i.e. 0.4mm, is still more than 37% for some level of input AC signal variation.

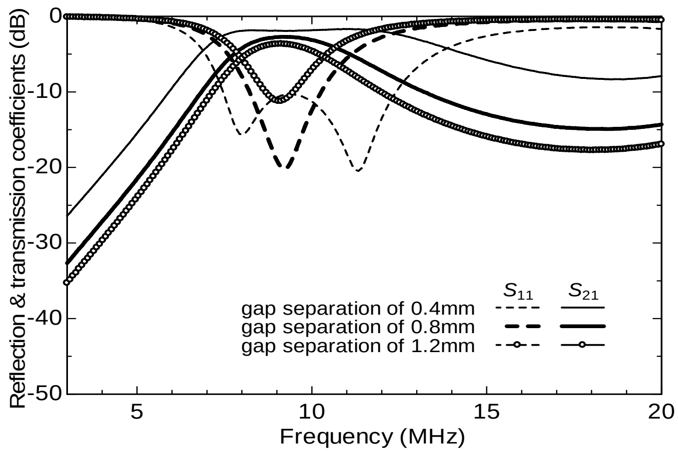

Figure 4. Measured scattering parameter of varied gap separation between 2 radiators [11]

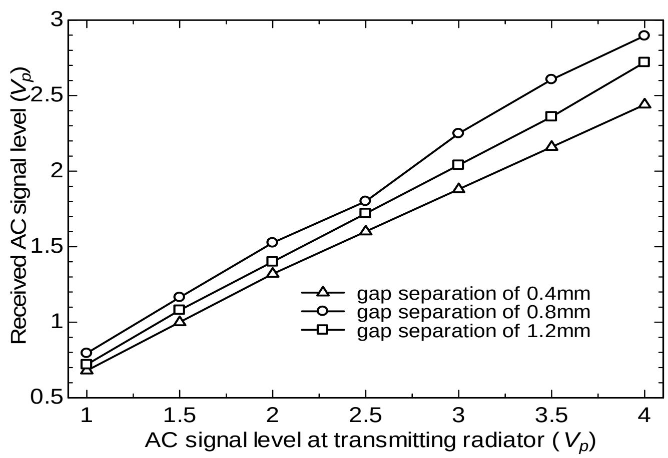

Figure 5. Measured results of received AC signal level at receiving radiator as variation of AC signal level at transmitting radiator for different gap separation

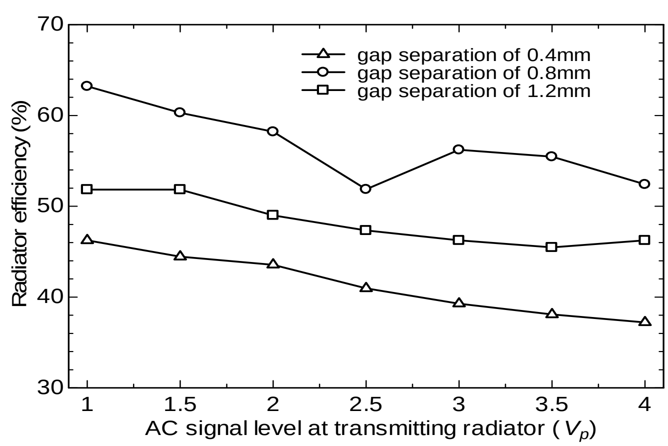

Figure 6. Radiator efficiency as variation of AC signal level at transmitting radiator for different gap separation

B. Characterization of Rectifier Circuit

The design of rectifier circuit configured with a voltage doubler involves the simulation as well as its implementation on printed circuit board (PCB). Figure 7 shows the pictures of realized rectifier circuit with surface mount device components used to satisfy the required space. The realized rectifier circuit is experimentally characterized by varying level and frequency of AC signal at the input port and then measuring the DC voltage produced by rectifier circuit at the output port. The measured results are plotted in Figures 8 and 9 for varied AC signal level and frequency, respectively, with the simulated results as comparison.

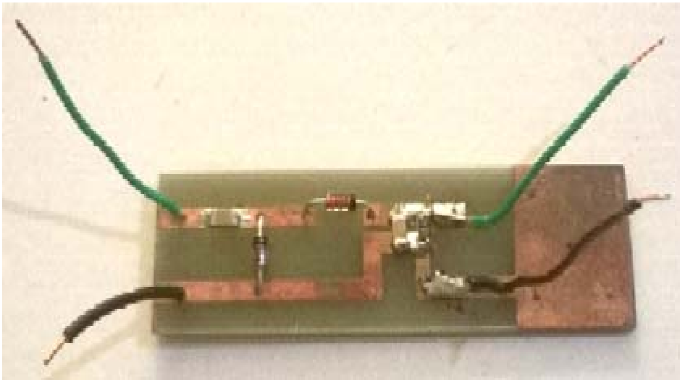

Figure 7. Picture of realized rectifier circuit

The measured results as variation of AC signal level shown in Figure 8 is seen coincided with the simulated results. In spite of DC voltage at the output port of rectifier circuit is less than twice of AC signal at the input port of rectifier circuit due to the voltage drop of diodes, however the DC voltage increases linearly as the AC signal level varies from 1 V_p to 4V_p at operating frequency of 10MHz. The overall voltage drops of diode are in the range of 1.22V-1.85V which also increase as the variation of AC signal level. Meanwhile, at the output port of rectifier circuit, the DC voltage is insensitive for the operating frequency varied from 8MHz to 12MHz as shown in Figure 9. It indicates that the deviation of DC voltage is less than 2% for the operating frequency of AC signal varied up to 20% from the center operating frequency of 10MHz.

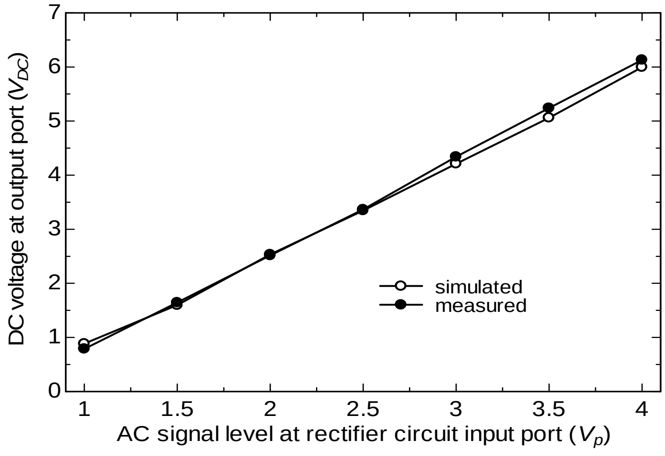

Figure 8. Measured DC voltage at output port of rectifier circuit as variation of AC signal level

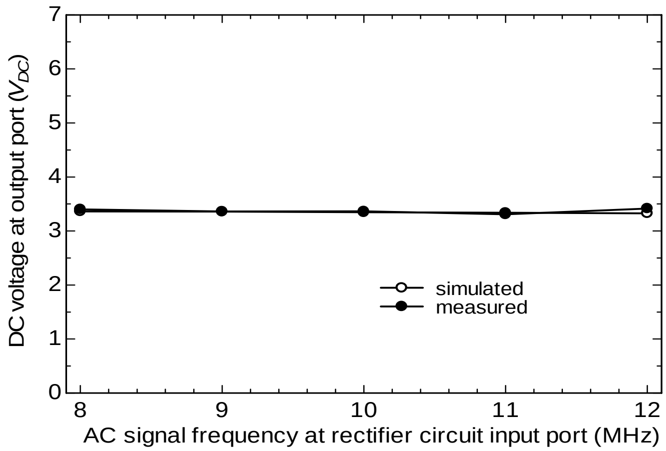

Figure 9. Measured DC voltage at output port of rectifier circuit as variation of AC signal frequency

C. Characterization of Wireless Power Charging Receiver

After performing the characterization for each part of wireless power charging receiver, then the performance of receiver in overall as an integration of receiving radiator and rectifier circuit is experimentally characterized. Both radiators are set with a certain gap in which the transmitting radiator is connected to the AC signal generator and the DC voltage is measured using a DC Voltmeter at the output port of rectifier circuit. The measured DC voltages as the variation of level and frequency of AC signal are depicted in Figures 10 and 11, respectively, for the gap separation between 2 radiators of 0.8mm and 1.2mm. Due to the low efficiency, the gap separation between 2 radiators of 0.4mm is not included in the measurement. As shown in Figure 10, although the increment of DC voltage is not as high as the result plotted in Figure 8 due to the efficiency of radiator, however the DC voltage for both gap separations still increases linearly as the variation of AC signal level.

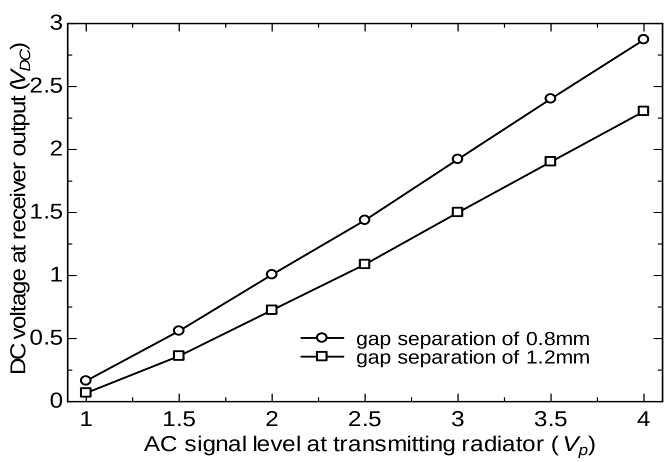

Figure 10. Measured DC voltage at output of wireless power charging receiver as variation of AC signal level

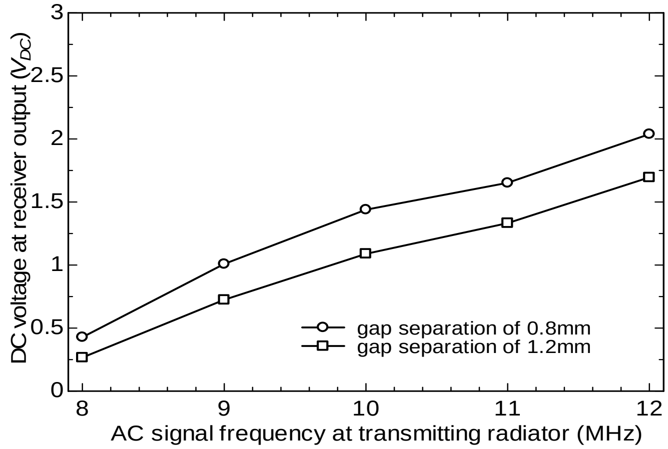

Figure 11. Measured DC voltage at output of wireless power charging receiver as variation of AC signal frequency

Meanwhile, the frequency variation of AC signal from 8MHz to 12MHz for both gap separations has affected the increase of DC voltage as indicated in Figure 11. This is probably evoked by the impedance mismatch of radiator which is becoming higher as the increase of input voltage frequency. From the results shown in Figures 10 and 11, the DC voltage at the output port of rectifier circuit is coincided with the efficiency of radiators shown in Figure 6 where the narrower gap separation the higher efficiency is obtained. In addition, the characterization for the integrated receiver system is realized by connecting a target mobile device to be charged at the output of receiver. The integrated system characterization is performed to check the feasibility of realized wireless power charging receiver in charging the target device. As demonstrated in Figure 12, when the signal generator is connected to the transmitting radiator with the gap separation between 2 radiators of 0.8mm, while the target mobile device, i.e. a mobile phone, is connected to the output of receiver, the measured DC voltage on the target mobile device is 4.12V_{DC} which is high enough to start charging the battery of mobile phone.

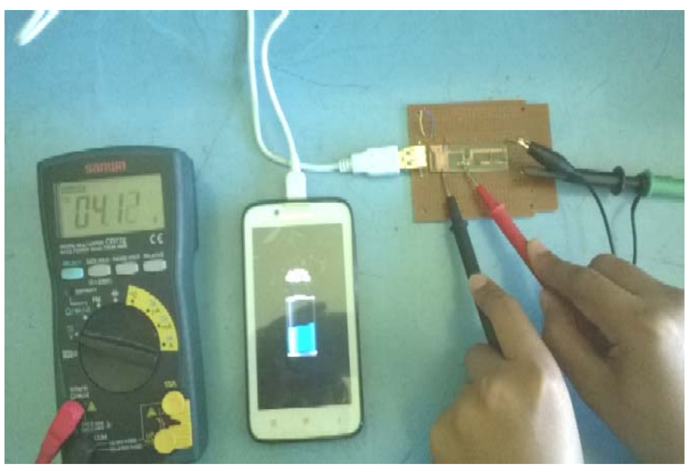

Figure 12. Characterization of integrated wireless power charging receiver

4. Conclusions

The characterization of wireless power charging receiver for mobile device which comprises of an electromagnetic waves radiator as a receiver of electrical energy and a rectifier circuit configured with a voltage doubler to produce DC voltage has been demonstrated. Some attempts to vary the level and frequency of AC signal in producing DC voltage have been carried out to investigate the performance of proposed wireless power charging receiver. From the measurement and characterization results, it has been found that the efficiency of radiator for a considerable gap was higher than 37% for some level of varied input AC signal. Meanwhile, the DC voltage at the output port of rectifier circuit has linearly risen only as the increase of AC signal level but not for the frequency change. A slight different of DC voltage at the output of receiver has occurred in the characterization of wireless power charging receiver integration for the frequency variation which is probably caused by the impedance mismatch on receiving radiator. It should be noted that the efficiency of radiators has played an important role to determine the performance of receiver. In addition, it has been demonstrated that the proposed wireless power charging receiver has successfully started charging a battery of mobile phone by producing $4.12V_{DC}$ at the output of receiver with 0.8mm gap separation between 2 radiators.

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