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Efficiency Enhancement of Wireless Power Transfer with Optimum Coupling Mechanism for Mid-range Operation

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Abstract – This paper depicts the design, implementation and analysis of efficient resonant based wireless power transfer (WPT) technique using three magnetic coupled coils. This work is suitable for mid ranged device due to small form factor while minimizing the loading effect. A multi turned loop size resonator is exploited for both the transmitter and receiver for longer distance. In this paper, class-E power amplifier (class-E PA) is introduced with an optimum power tracking mechanism of WPT system to enhance the power capability at mid-range with a flat gain. A robust method of finding optimum distance is derived with an experimental analysis of the designed system. In this method, the load sensitive issue of WPT is resolved by tuning coupling coefficient at considerable distances. Our designed PA with a drain efficiency of 77.8% for a maximum output of 5W is used with adopted tuning technique that improves the overall WPT system performance by 3 dB at various operating points.

Keywords: Wireless power transfer, Magnetic resonance, Coupling coefficient, Impedance matching, Power transfer efficiency

1. Introduction

Wireless power transfer (WPT) is an emerging technology that now substantially gaining more interest due to their contribution in technical fields such as bio-medical science[1, 2], electronic[3, 4] and automobile industry[5-7]. A WPT system majorly consists of magnetic coupled coils and matching circuits. The magnetic coupling between the transmitter (TX) and receiver (RX) actually depends on the input and output impedance condition which is inversely related to the distance [8]. Generally, the tunable LC impedance matching network is used to transform the overall circuit impedance, but lossy matching network increases the power loss and lowers the efficiency as well. In this study, a high efficient WPT system is designed using loop size TX and RX coils separated by a multi-turn planer shape repeater coil. The power transfer efficiency is optimized through the tuning of the coupling coefficient.

Until now, many efforts have been made to improve the WPT technology as well as its application which can be classified into three categories: electromagnetic induction [9-11], magnetic resonance [12-14], and microwave power transmission [15, 16]. Magnetic resonant coupling is considered the most suitable for WPT applications due to its high transmission range and efficiency compare to the induction coupling and microwaves[12]. In resonant coupled WPT, the transfer distance is actually limited due to reduced magnetic coupling with the axial separation between TX and RX coils. The effect of low couplings can be somewhat compensated by employing high quality factor 'Q' (Q= (1/R)(L/C)1/2) TX/RX coils[17]. Nonetheless, in practical WPT system Q-factor of coil becomes limited due to the loading effects of source/load resistances and ohmic losses of wire. Furthermore, high Q-factor cause the magnetic field of the circuit to rise due to high reactance and may cause adverse effects on human body [18]. WPT performance depends greatly on its design of TX circuit [19]. Position of the coils also greatly affects the impedance mismatch into the system, causing a loss of power transfer [20]. Our proposed tuning method at optimum position would help the matching between the coils in certain distances. In previous analysis, many complex circuitry and technique has been brought into account for the WPT system. In [21], a double channel power amplifier (PA) was proposed with a 15% efficiency enhancement for two coils indicating the changes of efficiency between coils position, hence loading effect. A 4coil analysis would be convoluted to track the optimum position compare to 3 coils and hence the application. Many of the previous work focused on the PA efficiency [21-23], dynamic load control [21], impedance matching [24-26], tunable inverter [27], etc. Most of these works enhanced the operation in PA, switching with multiple passive components that complicated the operation. In our work, we brought the simplicity of positioning the coil at its optimum coupling and hence improve the system

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efficiency. In general, class-E power amplifier (class-E PA)is used with the TX circuit which requires a single transistor to accomplish zero voltage switching (ZVS), makes the system simple and inexpensive [23]. Compare to other classes, it is more sensitive to the output impedance, requires fewer components with high reliability [21, 28]. In WPT, class-E PA is also used with a great of its achievement [19, 29]. In our proposed method a class-E PA is included with independent gate biasing with an optimum coupling matching technique. Coil alignment, load variation and distances between coils are some common factors in WPT for weaker transmission[30] which is considered into this study to minimizes the effect providing this technique. Moreover, the fundamental choice of considering three-coil WPT system is to enhance the energy efficiency that is stiffness against load variations and the reduced EMF emission induced by the coil misalignments[31]. In this work, a class-EPA is designed along with the matching circuit which includes TX coil as his load. Considering short ranged device for consumer electronics, a robust matching mechanism for three coils system was adopted for a longer distance.

The paper is organized as follows. General working principle of a class-E power amplifier is described in Section 2 followed by the implementation of a WPT system with repeater coil in Section 3. The content also includes the performance analysis of WPT system using coupling tuning technique to optimize the power transfer to the load in Section 4. The conclusion is provided in Section 5.

2. Principle of Class-E PA

Class-E PA is brought to minimize losses at active side of the experiment, to provide efficient high power transfer by the coil with high efficiency. The performance of the class-E PA generally depends on the load, quality factor, applied voltage, current, lumped ele ment and their conduction angle [23]. From a typical configuration of Fig. 1, that shows the working principles of class-E PA where a MOSFET (IRF530) is being chosen to perform the switching operation during 50% duty cycle to drive Class E amplifier over a conduction angle of 180°. From Drain supply voltage (VDD), DC power is provided to the PA through a radio frequency choke (RFC) L1, the VDD at Drain terminal from the DC supply was kept at 9 V to maintain the operating point within the conduction angle. Additionally, we put a shunt capacitor to compensate reactance of active device[29].

In order to obtain maximum output power, the output impedance of the class-E PA (L2 and C2) was kept as a conjugate matched with the Load (RL). In this work, we matched load resistance with 50Ω and MOSFET with lesser parasitic capacitor to provide sufficient power at the output. Load of the conventional class-E PA is further replaced by the TX of the WPT system to perform WPT operation. A detailed circuit configuration of conventional class-E PA is given in Fig. 2. Choosing a high quality factor (QL), the values of C and L are calculated according to Firas [32].

$$R = 0.5768\left(\frac{V_{DD}^2}{P_{out}}\right)\left(1-\frac{0.451759}{Q_L}-\frac{0.402444}{Q_L^2}\right) \quad (1)$$

$$C = \frac{1}{5.44658\omega R}\left(1+\frac{0.91424}{Q_L}-\frac{1.03175}{Q_L^2}\right)+\frac{0.6}{\omega^2 L} \quad (2)$$

$$L = \frac{Q_L R}{\omega} \quad (3)$$

Where, ω is the resonant frequency of the WPT system, L is the radio frequency choke, C is the shunt capacitor and R is the load resistance to be calculated. Circuit operation of class-E PAis considered the general switch mode PA to reduce the loss of the system and to provide sufficient power to the load. To maintain the impedance matching, ADS (Advanced Digital System) software is used for a complex load of RLC. Biasing at gate terminal ensured the MOSFET switching at operating point. L1, C1 of Fig. 1, is kept for L matching filtering at the primary side.

Operating frequency is selected at 4.89 MHz and component values of matching filters from Fig. 2, areL1= 0.6 μH, C1= 0.225 nF, L4= 3.14 μH, C4= 0.3 nF, C5= 2.2 nF, and C6 = 1.12 nF. The value of 12 μH and 22 μH are selected for the RFC coils L2and L3, respectively. The

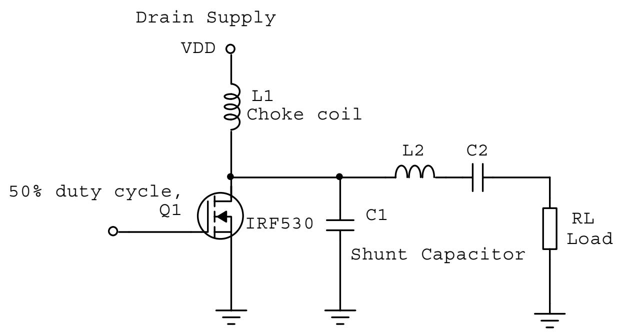


Fig. 1. Schematic diagram of the Class-E power amplifier

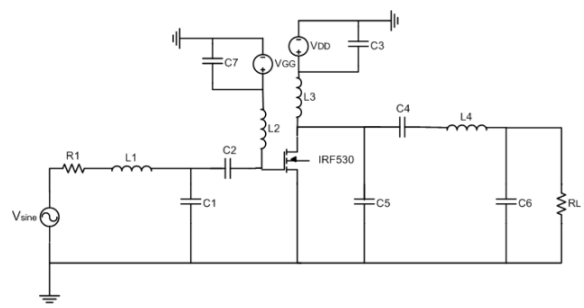


Fig. 2. Experimental prototype of the Class-E power amplifier

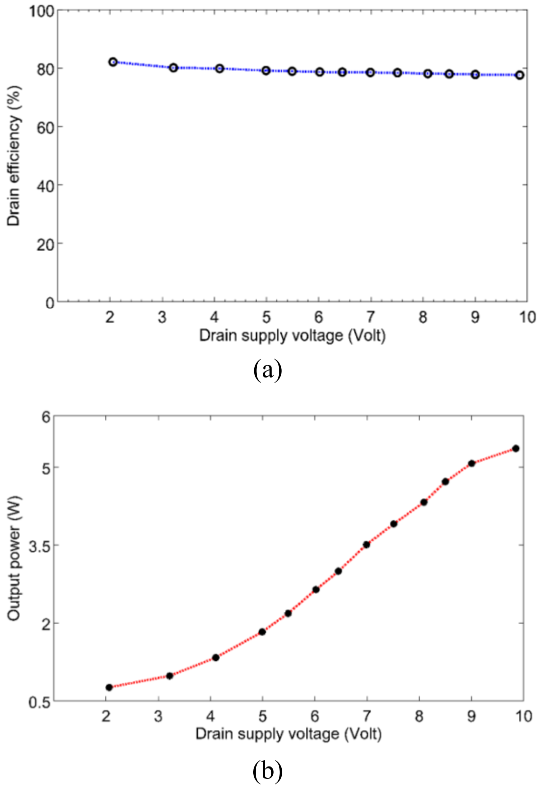


Fig. 3. (a) Measured drain efficiency and (b) output power versus drain supply

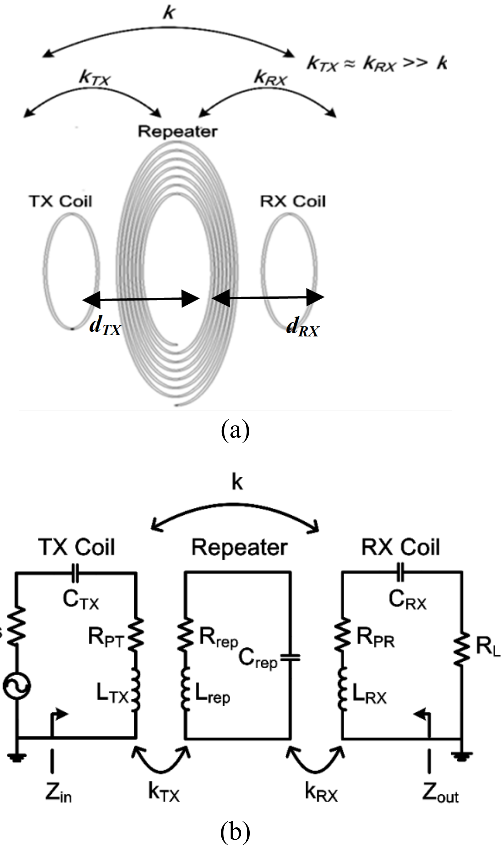


Fig. 4. (a) Schematic of resonant coupled WPT system with a repeater (b) Electrical circuit model of WPT

performance and output power of the implemented class-E PA (Fig. 3) are measured and analyzed by energized the circuit at 4.89 MHz using HP8675A generator. Fig. 3 shows steady drain efficiency. In this study of using a PA with WPT system the drain supply voltage of PA is kept VDD=9 V for a design of output power 5 W. Drain efficiency is observed 77.8%.

3. WPT System with Repeater

Unlike four coils transmission system in WPT, 3 coils resonant WPT contributes the simplicity with a considerable trade-off between efficiency and distance. A general model of RCWPT model with an intermediate multi-turn coil is depicted in Fig. 4 (a), TX and RX coils are used with a single turn to avoid the self and parasitic capacitances that can mismatch impedance on both TX and RX sides. Resonating operations are kept in R-L-C series combination at both sides. Targeted Energy transfer is modeled with a total distance (d) between the TX and RX coil. A repeater coil enhanced the distance (where, total distance $d= d_{TX} + d_{RX}$ in Fig. 4(a)) whereas, PTE degrades sharply by a slight increment of distance. In this study of three coil WPT system, a robust technique of tuning mechanism is described to enhance the system performance. To understand the key interaction between the coils, one can anticipate the coils connected with spring to each another, a weak coupling will provide high efficiency with moderate distance energy transfer and vice versa. High efficiency is achieved at resonance, while all the coils are able to induce magnetic flux to transfer the energy to the load. As the coupling coefficient comes as a function of power transfer and also coupling coefficient depends on variable parameters and distance mainly, so that the PTE can be maximized by providing the adequate tuning between the coils. All coils are provided with high quality factor (Q) and the coupling coefficients are kept low to transfer the power easily. In the circuit arrangement, AC voltage source and Series resistance (R_S) represent the class-E PA output which energize the TX coil at the driving frequency same as the resonant frequency of the coils. As because the loading effect degrades the performance that can be reduced by a factor of $\omega^2 M/R$ (M = mutual inductance) using feeding loops as TX/RX coils with a multi-turn resonator as a magnetic repeater between them [12-14]. The intermediate resonator, relay the magnetic field from TX to RX, and would easily improve the magnetic coupling at long distance. Cross coupling between TX and RX is ignored due to its small value relative to coupling coefficient between TX and repeater (k_{TX}) coil and repeater to RX coil (k_{RX}).

To analyze the working model of a simple 3coil structure is shown in Fig. 4, where all the coils are considered as flat spiral to avoid the parasitic lumped elements. R_{PT}, R_{rep} and

R_{PR} are the intrinsic resistance of TX, Repeater and RX coil respectively. R_L and R_S are the load and source resistance. L_x and C_x(x=TX, rep and RX) are connected in series. C_{TX}, C_{rep} and C_{RX} are the resonant capacitors of TX, Repeater and RX coil respectively. Resonant capacitances were kept constant with an operating frequency 4.89 MHz. C_{TX} is considered as output matching network of class-E PA along with the parasitic capacitance of resonator. Besides of this model, an RF power amplifier is designed to get a 3dB gain with a drain efficiency of 77.8 %. Considering the Biot-Savart's Law of current carrying conductor, an alternating current (AC) is introduced by the signal generator to get an oscillating magnetic field that can store the energy in L_{TX} and induced electro motive force (e.m.f) in L_{rep} and finally transferred into L_{RX}. Mutual inductance between the coils can be found through Neumann's formula;

$$M_{XY} \cong \frac{\pi\mu N_X N_Y r_X^2 r_Y^2}{2\left(d_{XY}^2 + r_Y^2\right)^{\frac{3}{2}}} \quad (4)$$

Where, M_{xy} is the mutual inductance between two coil, N_x, N_y are the turn number of primary and secondary coil respectively, similarly r_x, r_y is the radius of the primary and secondary coil. d_{xy} is the distance between them. Lumped elements like inductor and capacitor consist of imaginary value which behaves as a lossy element in WPT. Thus, it is required to operate the whole WPT system with its resonant frequency to consider maximum power transfer. In this work, resonant frequency (f_0) is kept such as;

$$\omega_0 = 2\pi f_0 = 1\Big/\sqrt{L_{TX}C_{TX}} = 1\Big/\sqrt{L_{rep}C_{rep}} = 1\Big/\sqrt{L_{RX}C_{RX}} \quad (5)$$

According to Kirchhoff's voltage law (KVL) applied into this electrical circuit model in Fig. 4(b) are;

$$\left(\frac{R_{TX}}{j\omega L_{TX}} + 1 - \frac{\omega_0^2}{\omega^2}\right) I_{TX} + k_{TX}\sqrt{\frac{L_{rep}}{L_{TX}}} I_{rep} = \frac{V_S}{j\omega L_{TX}} \quad (6)$$

$$k_{TX}\sqrt{\frac{L_{TX}}{L_{rep}}} I_{TX} + \left(\frac{R_{rep}}{j\omega L_{rep}} + 1 - \frac{\omega_0^2}{\omega^2}\right) I_{rep} + k_{RX}\sqrt{\frac{L_{RX}}{L_{rep}}} I_{RX} = 0 \quad (7)$$

$$k_{RX}\sqrt{\frac{L_{rep}}{L_{RX}}} I_{rep} + \left(\frac{R_{RX}}{j\omega L_{RX}} + 1 - \frac{\omega_0^2}{\omega^2}\right) I_{RX} = 0 \quad (8)$$

where, R_x,L_x, C_x,I_x *and* k_x is the total resistance, coil inductance, resonant capacitance, coil current and coupling coefficient of respective x=TX/RX/rep. Here, $R_{TX} = R_S + R_{PT}$ and $R_{RX} = R_L + R_{PR}$, at resonance, considering $\omega = \omega_0$ we can get,

$$j\omega_0 L_{TX} + \frac{1}{j\omega_0 C_{TX}} = j\omega_0 L_{rep} + \frac{1}{j\omega_0 C_{rep}} = j\omega_0 L_{RX} + \frac{1}{j\omega_0 C_{RX}} = 0 \quad (9)$$

Finally Eq. (6), (7) and (8) can be deduced to a matrix form as below;

$$\begin{bmatrix} Z_T & k_{TX}\sqrt{\frac{L_{rep}}{L_{TX}}} & 0 \\ k_{TX}\sqrt{\frac{L_{TX}}{L_{rep}}} & Z_{rep} & k_{RX}\sqrt{\frac{L_{RX}}{L_{rep}}} \\ 0 & k_{RX}\sqrt{\frac{L_{rep}}{L_{RX}}} & Z_R \end{bmatrix} \begin{bmatrix} I_{TX} \\ I_{rep} \\ I_{RX} \end{bmatrix} = \begin{bmatrix} \frac{V_S}{j\omega_0 L_{TX}} \\ 0 \\ 0 \end{bmatrix} \quad (10)$$

Where, $Z_X = R_x \big/ j\omega_0 L_X$ represents the transformed impedance ratio of each coil (x = TX/ RX/rep). From eq. (10), load current can be derived as;

$$I_{RX} = -\frac{V_S k_{TX} k_{RX} Q_{TX} Q_{rep} Q_{RX} \cdot \frac{1}{\sqrt{L_{TX}L_{RX}}}}{\omega_0 (1 + k_{TX}^2 Q_{TX} Q_{rep} + k_{RX}^2 Q_{rep} Q_{RX})} \quad (11)$$

Eq. (11) indicates that the performance of the repeater independent of the individual RLC values rather depends on the Q-factor of each coil (Q_x=Q factor of x coil, where x = TX/ RX/ rep). Thus, load voltage V_L can be found as, $V_L = -I_{RX} \times R_L$. In a conventional method of analysis, it is required to understand the forward wave transmission (S_{21}) between the resonant coupled coils. Considering TX and RX coil to transmit the power for 3 coil system $|S_{21}|$ can be calculated [13] as followed

$$|S_{21}| = 2\frac{V_L}{V_S}\sqrt{\frac{R_S}{R_L}} \quad (12)$$

PNA-X (Keysight- N-5241A) is used to measure the practical coupling coefficient k_{TX} and k_{RX} for the measured distance. In a typical analysis, the $|S_{21}|$can be found as

$$|S_{21}| = \left[\frac{2k_{TX}k_{RX}Q_{rep}\sqrt{Q_{TX}Q_{RX}}}{1 + k_{TX}^2 Q_{TX} Q_{rep} + k_{RX}^2 Q_{rep} Q_{RX}}\right]\sqrt{\frac{R_L R_G}{R_{TX}R_{RX}}} \quad (13)$$

where, $R_G = R_S + R_{PT}$ and $R_{RX} = R_L + R_{PR}$ indicating the total input and output resistance of TX and RX coil respectively. The theoretical graph with respect to distances can be found by evaluating Eq. (13) as Fig. 5 below.

To evaluate the coil transfer efficiency, it is necessary to take account the power dissipation in TX and RX as well

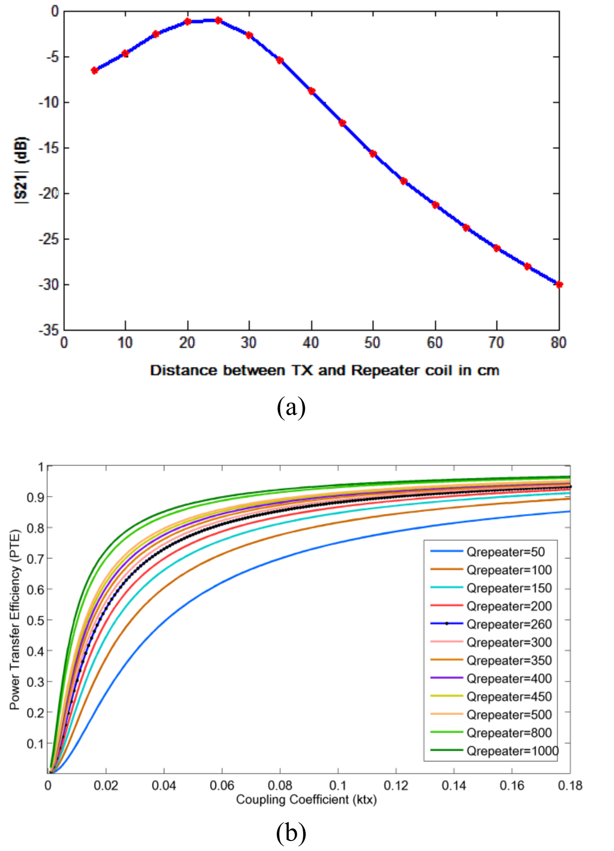


Fig. 5. (a) Theoretical analysis of $|S_{21}|(dB)$ versus distance (cm) between TX and Repeater coils; (b) theoretical PTE versus k_{TX} for different Q_{rep}

as the power transferred to the load. Under the given value of source and load resistances, the coupling between the TX and repeater is tuned as a function of the repeater-to-RX coupling which maximizes the efficiency. The coil transfer efficiency η_{PTE} of the WPT system can be stated computing each of the coil efficiency where;

$$\eta_{PTE} = \eta_{TX} * \eta_{rep} * \eta_{RX}$$
$$= \frac{k_{TX}^2 k_{RX}^2 Q_{rep}^2 Q_{TX} Q_{RX}}{\left[\left(\frac{R_{PT}}{R_G}\right)\left(1+k_{RX}^2 Q_{rep} Q_{RX}\right)+\left(k_{TX}^2 Q_{TX} Q_{rep}\right)\right] * \left[1+k_{RX}^2 Q_{rep} Q_{RX}\right]} \tag{14}$$

Here, η_{TX} , η_{rep} and η_{RX} are the efficiency of TX, repeater and RX coil respectively. From Eq. (14) it is clear that, the coupling coefficients and Q_{rep} plays fundamental role for a good power transmission. A theoretical analysis of PTE versus k_{TX} and Q_{rep} shows in Fig. 5. From the graph, it is observed that weak coupling between the TX to repeater coil provides a better performance with a selected Q_{rep}. Typically, the majority of power loss occurs in TX section rather than the repeater. It is because the loss in TX coil consists of coil conductor loss along with the driving circuitry losses, whereas the repeater loss contains only conductor loss. So that, overall performance greatly depends on the η_{rep} whereas;

$$\eta_{PTE} \cong \eta_{rep} = \frac{k_{RX}^2 Q_{rep} Q_{RX}}{1+k_{RX}^2 Q_{rep} Q_{RX}} \tag{15}$$

Therefore, it is necessary to minimize Eq. (14) for achieving high power transmission on the load. This can be achieved by optimum tuning of the Repeater to RX coupling according to the axial orientation between the repeater and RX coils. Taking the first derivative the optimum coupling coefficient of k_{RX} can be stated from

$$\frac{\partial}{\partial k'}(\eta_{PTE}) = 0 \tag{16}$$

Where, $k' = k_{RX}^2 Q_{rep} Q_{RX}$. Hence, the optimum position between the repeater coils to RX coil for maximum efficiency is found;

$$k_{RX(opt.)} = \frac{1}{\sqrt{Q_{RX} Q_{rep}}}\left[\frac{k_{TX}^2 Q_{TX} Q_{rep}}{\left(\frac{R_{PT}}{R_S}\right)}+1\right]^{1/4} \tag{17}$$

Where, $k_{RX\,(Opt.)}$ is the optimum coupling coefficient at a particular optimum position between repeater and RX coil. The power transmission and efficiency typically degrade when the position of the conventional repeater significantly deviated from the midpoint between the TX and RX coils[33]. However, the proposed flexible position tuning prevents the performance degradations and ensures adequate impedance matching without changing the original resonant frequency of the system. The optimum tuning coupling coefficient in Eq. (17) is chosen to ensure the WPT system operates with proper input and output impedances for any desired load (In this study 50 Ω). Fig. 6 illustrates experimental setup of resonant coupled WPT

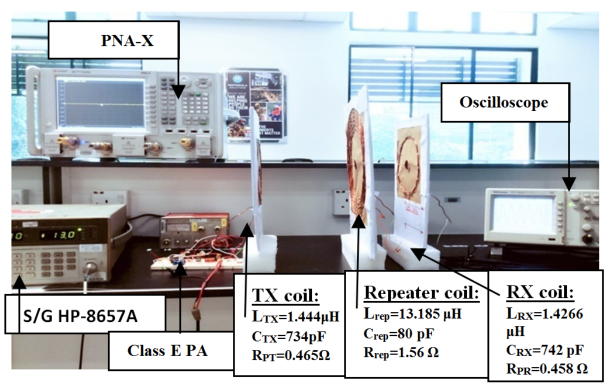


Fig. 6. Experimental setup of the WPT system including transmitter, receiver and a repeater coil placed at the center

Table 1. Coils specification of wpt experiment

Coil parameters	TX coil	RX coil	Repeater coil	Remark
Coil Radius (cm)	7.25	7.25	14.5	Mean radius
Turn number	2	2	6.5	Planar spiral
Pitch (cm)	0.25	0.25	1	AWG 18
Coil inductance (μH)	1.444	1.4266	13.185	Measured
Resonant Capacitance (pF)	734	742	80	Measured
Parasitic resistance	0.465 Ω	0.458 Ω	1.55 Ω	Measured
Q-factor	0.887	0.877	260	Calculated

with a repeater coil placed at the center between the TX and RX coils. Both the TX and RX coils are designed as loop resonators having 14.5 cm of outer diameter and 0.25 cm of pitch distance. Coils specifications are given below in Table 1.

4. WPT Performance Analysis

An overall experimental design studied considering the condition of short ranged device for consumer electronics for better power transmission due to load sensitivity. As impedance mismatch occurs greatly by the position of coil, this method will enhance the feasibility of flat gain power transfer for a short range operation. The performance of the overall WPT system (including the class-E PA) is shown in Figs. 7, 8 and 9 for a coupling distance from 5 to 60 cm. Distance is studied between the TX to repeater coils. The WPT system's output was extracted providing a signal generator (V_{GG}) with +13dB of AC input (Fig. 2). Performance in need of class-E PA is analyzed in Fig. 7, where at fixed and optimum case is measured considering the power amplifier's effect into the system which brought a 7.42% better performance at a longer distance (50 cm) compare to close distance of 10cm. Performance is analyzed with and without PA at optimum and fixed coupling. Eq. (17) depicts the optimum coupling equation to find the optimum position between TX to Repeater to RX coil. At first, each of the position, k_{TX} is fixed while k_{RX} is also fixed at a fixed coupling coefficient of 0.137. All coupling coefficient is measured using PNA-X (Keysight N5241A). Secondly, each of the increment of distance was kept k_{RX} at optimum tuning followed by Eq. (17). While the position increased each time, due to the load sensitivity the overall impedance mismatch occurs into the WPT system which is further matched by considering the optimum distance. At 20 cm, S_{21} (dB) reaches its maximum point for the system. Class-E PA used into this work shows its significance at a distance between 5 cm to 30 cm where using optimum coupling technique using PA shows a flat rate of power transfer in Fig.8, which signifies the necessity of PA for the system. In Fig. 8, about 18.61% better coil transfer efficiency is significant at close distance and 7.91% at mid-range. Nonetheless, short ranged hand hold products will be benefitted wisely by using 3 coils system with an optimum tuning function that is observing through the graph line between using PA at optimum coupling condition.

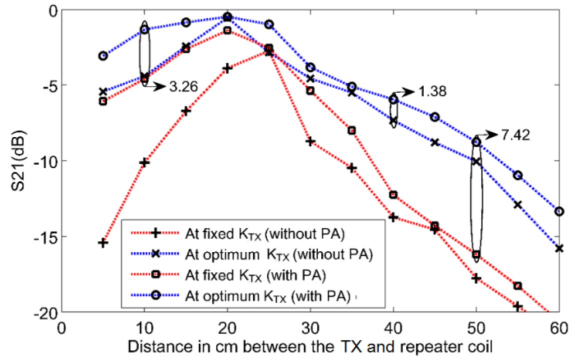


Fig. 7. Measured S_{21} for the WPT system including repeater coil supplied via the designed Class-E power amplifier

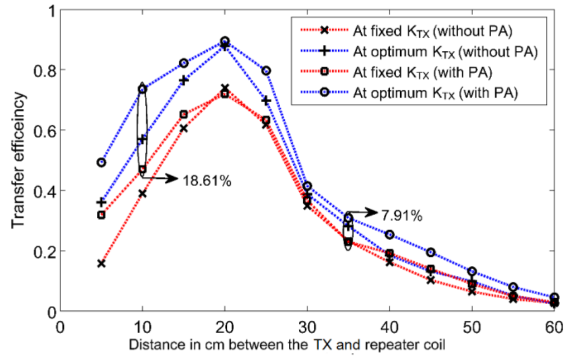


Fig. 8. Measured power transfer efficiency of the WPT arrangement loaded with 50 Ω.

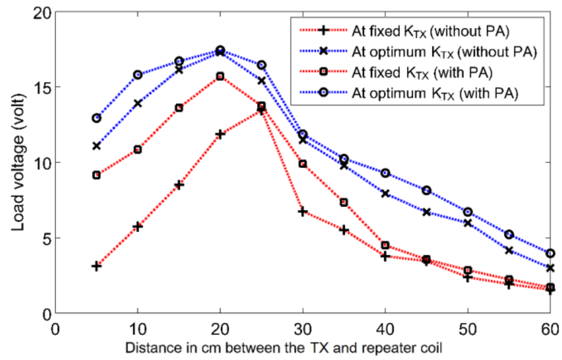


Fig. 9. Measured data of Extracted load voltage from the designed WPT system

From the $|S_{21}|$(dB) graph it is inevitable that the maximum PTE will follow the operation according to Eq. (14), by choosing the maximum point considering the *k'* at Eq. (16), which is at 20 cm followed in both Fig. 7 and Fig. 8. From 15 cm to 25 cm, behavior of PTE shows the steadfast graph which is required for short ranged device.

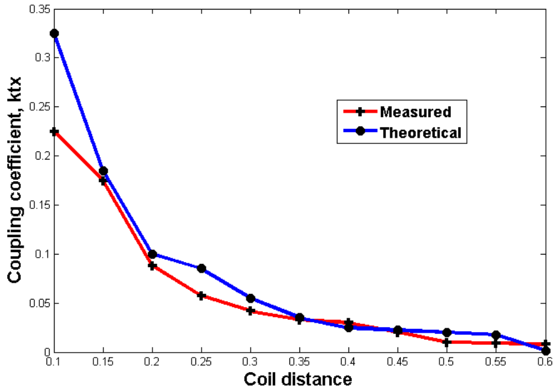


Fig. 10. Coupling coefficient k_{tx} versus coil separation between TX and repeater coil

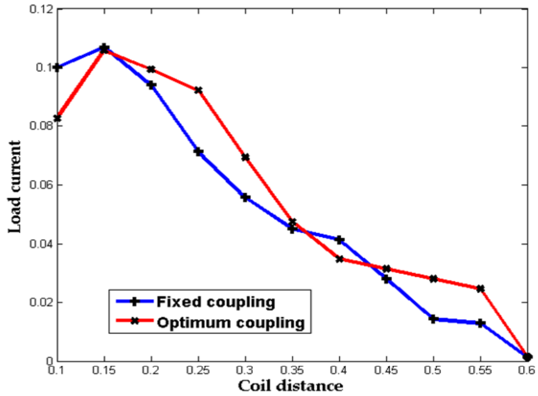
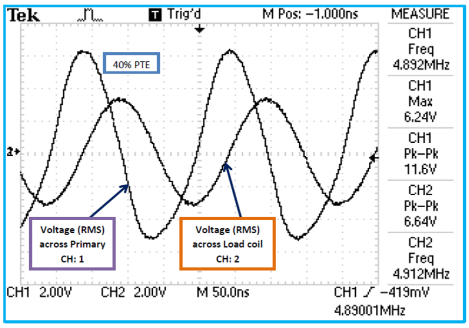
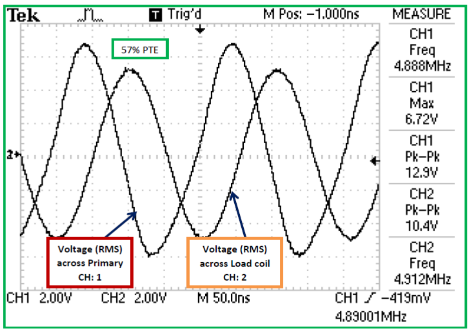


Fig.11. Load current at fixed and optimum coupling positioning

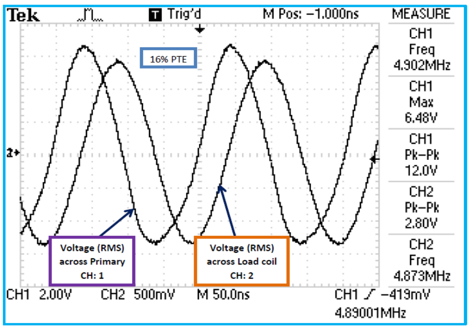


(i) At fixed k_{TX}

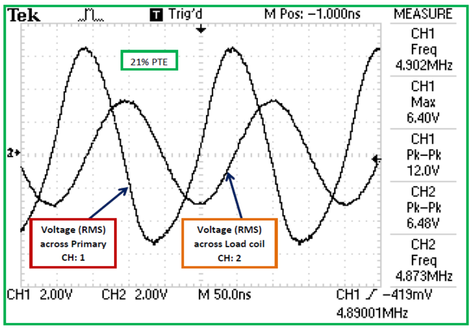


(ii) At optimum k_{TX}

(a) Distance = 10 cm



(i) At fixed k_{TX}



(ii) At optimum k_{TX}

(b) Distance = 45 cm

Fig. 12. Measured voltage waveforms for resonant coupled WPT system operating at (i) fixed coupling, and (ii) optimum coupling for (a) 10 cm distance; (b) 45 cm distance between the repeater and TX coils (Here, CH1 and CH2 are representing the input and output voltages, respectively)

As it is shown that PTE greatly depends on Q_{rep} and k_{RX} in Eq. (15), each time of increasing TX to repeater value will greatly depend on Q_{rep} and k_{RX}. In this work, we fixed the Q_{rep} by choosing a flat spiral coil to vary k_{RX} at optimum distance. Load voltage steadiness can also be observed in Fig. 9, for a greater distance. Performance increased significantly using PA at the transmitter end with a proper matching of output impedance. Eq. (11) and (14) further explains the performance of the WPT degradation rapidly when the TX coil axially moves away from the repeater. The best performance of the system achieves through the optimum tuning of TX-to-repeater coupling k_{TX} according to the axial orientation between the repeater and RX coils. This is because, the output impedances of the PA changes with the coupling k_{TX}, resulting in a non-optimal operating condition of the PA. The tuning of k_{TX} was practically implemented by adjusting the distance between the TX and repeater coils within 4 to 8 cm as a function of the coupling distance variation between the repeater and RX coils. The results in Fig. 7 and Fig. 8 experimentally validate the effectiveness of the proposed technique.

As seen in Fig. 8, the adaptive tuning technique shows better efficiency than the system with fixed k_{TX}, and can deliver 4.1 W to the load at 20 cm with a coil transfer efficiency of 89%. The same situation experiences for the extracted load voltages shown in Fig. 9. The input-output waveform graphs for the designed WPT system supplied by class-E PA are also illustrated for both fixed and optimum k_{TX}. Load current data at fixed and optimum position can be found from Eqs. (10), (11) and (17). Considering the real time positioning of coil, load current depends on the coupling coefficient whereas, mutual coupling between coils changes due to the coil separation. Using Eq. (4), a graph is presented in Fig. 10 comparing with measured data to see the behavior of coupling coefficient (of the taken dimension of coil) versus distances.

Finally, the load current graph can also be determined at fixed and optimum tuning of k_{rx} in Fig. 11,

During the weak coupling region after a distance of 20cm, the optimum coupling dominates in fig. 11 to show the effect without class-E PA. However, at 40cm to 55 cm of mid-range operation the quality enhanced about 5times using the optimum tuning. The enhancement follows Eq. (11) and (17), where the load current is related with the coupling coefficient and optimum coupling distance. Considering Eq. (10), a similar equation can be established also for I_{TX}, to observe the coil transfer efficiency. In Fig.12, the actual graph was taken from the oscilloscope at closed and mid-range distance, keeping the load voltage at channel 2 of the oscilloscope and input voltage in channel 1. It has been observed into the fixed and optimum tuning condition at each of the fixed distance between TX to Repeater distances. While in matching condition, the output of the load voltage shows a significant improvement while keeping the same arrangement but in optimum coupling condition. Frequency of operation was kept constant for the whole experiment.

5. Conclusion

In this study, a high efficient resonant based WPT system has been designed including a developed class-E PA operation with robust impedance matching technique. Loop-shaped TX and RX coils with a flat planner spiral magnetic repeater coil are used to extend the power transfer capability of the WPT system. Our designed class-E PA with the matching circuit acts as the DC-AC inverter for the WPT system and achieves significant improvement using the optimum tuning method. In this design, MOSFET is chosen to reduce switching loss, yielding better efficiency. To improve the circuit efficiency, low loss and high quality passive components are used. The matching networks enable the circuit to operate at the adequate input and output impedance conditions. A fixed 50 Ω load is used with RX coil to avoid ambiguous change in WPT system instead of load variation. To achieve the best efficiency and output power, an optimum tuning of repeater coil positions is also proposed. With this optimum tuning, the measured performance was improved by more than 3 dB at a different operating distance and a successful flat transmission of power is observed for a distance over 5 to 25 cm for the application at consumer electronics. Load sensitive issue is resolved by choosing the optimum distance to provide maximum power at optimum coupling condition.

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