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Energy Transfer by Resonance Coupling

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ABSTRACT

This paper presents the research work focusing on the possibility to transmit power with a high power densitiy and a high efficiency. The applications of power supply require a smaller size, lower weight with a good energy on-board management. This work shows not only the possibility of wireless power transfer, but also the biological effect is taken into account for the safety precaution of human use. The system is described and set up using the resonance coupling effect and impedance adaption for multi-stage conversion. The transmitting power up to 180W is applied at a frequency of 6.78 MHz across a gap in the range between 30 mm to 80 mm. The experimental results show that the maximum efficiency up to 88 % has been achieved. The maximum transmitted power density reaches up to 0.14 W/mm^2. High power can be transmitted using resonant coupling with high efficiency. Coupling coil characteristics significantly affect wireless power system losses. High power density of the active areas can be in the high range of 0.14 W/mm^2. Resonance coupling can be applied in short range applications keeping EMC and EMF restrictions.

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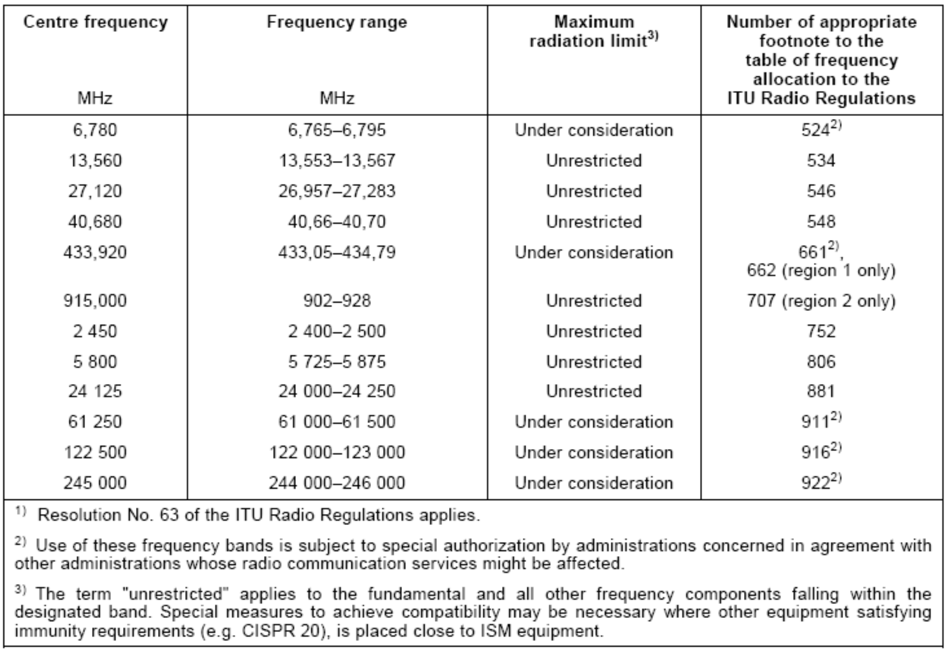
1. INTRODUCTION

Wireless power transmission offers a way to avoid the cumbersome power cable and offers more safety in case of devices where high voltage sources such as 230 Vac should be avoided. But the major disadvantages of existing wireless power transmissions are [1-3] low efficiency, typical < 40%, low power density as 0.004 W/cm$^{2,\,-}$ not considering biological effects, large and heavy equipment andonly low amount of power transmissible. Therefore, this research proposes the wireless energy transfer by resonance coupling with the high power density to achieve a smaller size together with high efficiency. Due to the methodology, the biological effect can be neglected; the system complies with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) regulations [5]. The principle in this research is to use the evanescent wave coupling like described in [1]: Using a set-up, consisting of two wire coils each with a diameter of 60 cm, and a coil which transforms the energy to the load (a bulb), to show that it is feasible to send power over a distance of two meters. The primary coil is connected to a RF power source and the secondary supplies via a coupling coil the light bulb. The main advantage here is the resistive load of the bulb to the coils as that way the matching impedance can be optimized easily. This system is based on resonant coupling,the coils resonate at a frequency of 10 MHz. The idea is to use a resonant wave coupling to avoid that the energy in the near field does propagate through the air. In a near field area evanescent waves carry no energy, it is a near field standing wave which decays exponentially with the distance. In this first demonstration, the researchers showed that the scheme can transfer power with an efficiency of 45 percent [1].Evanescent wave coupling is basically identical to the near field interaction in electromagnetic field theory. Depending on the transmitter impedance contributions either capacitive or inductive, the wave is either predominantly electric or magnetic. The particular concept in this research is the combination of the relative low operating frequency of 6.78 MHz which corresponds with a large wave length compared to the size of the antenna, a selected ferrite material which has its resistive contribution of the complex permeability above the operation frequency and the selection of the resonance coupling devices that way that the near field coupling effect allows a maximum of efficiency.

2. EMF AND CONSIDERATIONS AND RELATED BIO EFFECT

The directional power propagation in terms of electromagnetic compliance associated with the safety of human is taken into account. For keeping the EMC requirement the CISPR 11 standard for industrial, scientific and medical (ISM) equipment is considered for the system design. CISPR 11 defines ISM-designated frequency bands which are exempted from emission requirements. This means that there are no radiation limitsatcertainfrequency ranges. One range defined at Table 1 of CISPR 11 is from 6.765 MHz to 6.795 MHz with a center frequency of 6.780 MHz [4] as shown in Table 1 and used for the present design.

Table 1. Frequency designed by ITU for use as fundamental ISM frequencies



Centre frequency MHz	Frequency range MHz	Maximum radiation limit[3]	Number of appropriate footnote to the table of frequency allocation to the ITU Radio Regulations
6,780	6,765–6,795	Under consideration	524[2]
13,560	13,553–13,567	Unrestricted	534
27,120	26,957–27,283	Unrestricted	546
40,680	40,66–40,70	Unrestricted	548
433,920	433,05–434,79	Under consideration	661[2], 662 (region 1 only)
915,000	902–928	Unrestricted	707 (region 2 only)
2 450	2 400–2 500	Unrestricted	752
5 800	5 725–5 875	Unrestricted	806
24 125	24 000–24 250	Unrestricted	881
61 250	61 000–61 500	Under consideration	911[2]
122 500	122 000–123 000	Under consideration	916[2]
245 000	244 000–246 000	Under consideration	922[2]

[1] Resolution No. 63 of the ITU Radio Regulations applies.

[2] Use of these frequency bands is subject to special authorization by administrations concerned in agreement with other administrations whose radio communication services might be affected.

[3] The term "unrestricted" applies to the fundamental and all other frequency components falling within the designated band. Special measures to achieve compatibility may be necessary where other equipment satisfying immunity requirements (e.g. CISPR 20), is placed close to ISM equipment.

Todayit is a must for a state of the art product to consider the biological effect on human body. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) publishes guidelines for limiting RF exposure that provides protection against known adverse health effects [5]. According to the ICNIRP Guidelines an adverse health effect causes detectable impairment of the health of the exposed individual or of his or her off-spring. In this work it can be shown that the field used to transfer the power is limited to the area between transmitter and receiver and thus outside of the beam has less biological effect as shown in Figure 1 [7]. The set-up shown here can even keep the limit level of0.1 µT which is the lowest level starting at a frequency of 10 MHz and going up to 300 MHz as shown in Figure 1 [4].

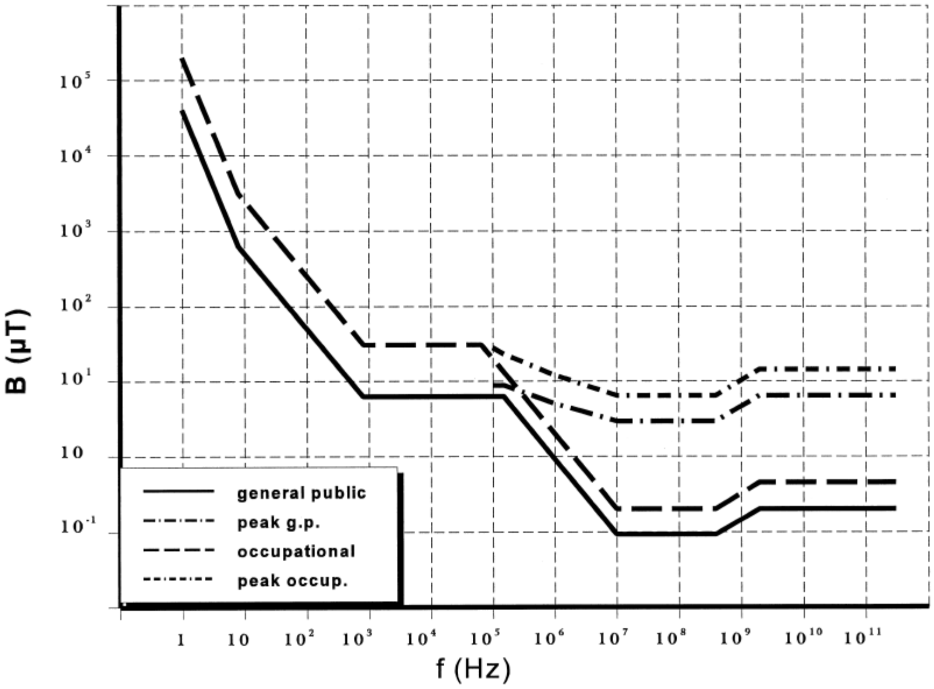


Figure 1. ICNIRP limits of magnetic flux density exposure to human body

3. PROPOSED PRINCIPLE OF WIRELESS POWER TRANSMISSION

3.1. Resonance Phenomena

This concept uses resonant circuits to transmit the power at a specific frequency from the transmitter to the receiver based on the electromagnetic resonance. The example of frequency resonant is shown in Figure 2 [6] and [9].

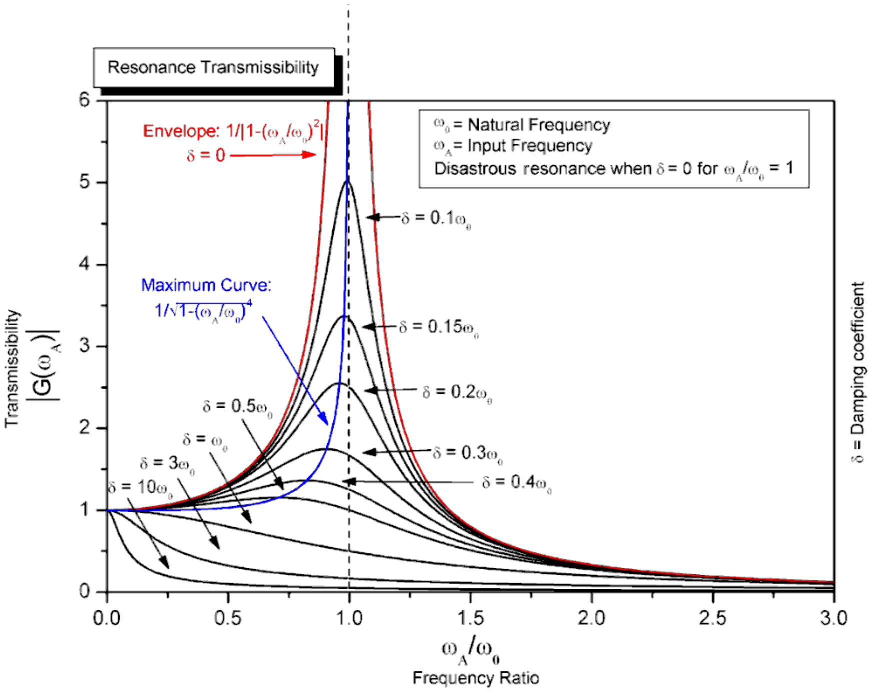


Figure 2. The frequency resonance phenomena

$\frac{\omega_a}{\omega_0}$, the frequency ratio represents the deviation from the center frequency, normalized to the "Natural Frequency". $\left|G_{(\omega_a)}\right|$ here the so called transmissibility is the resonance ability and has its maximum at the center frequency of the circuit where the natural frequency equals the input frequency. In an ideal system the value of the transmissibility is ∞ at $\frac{\omega_a}{\omega_0} = 1$. In a non-ideal system with resistive losses or where the system emits its energy partly the transmissibility reaches its maximum at the same frequency but the value limits in dependence of the losses which results is lower efficiency.

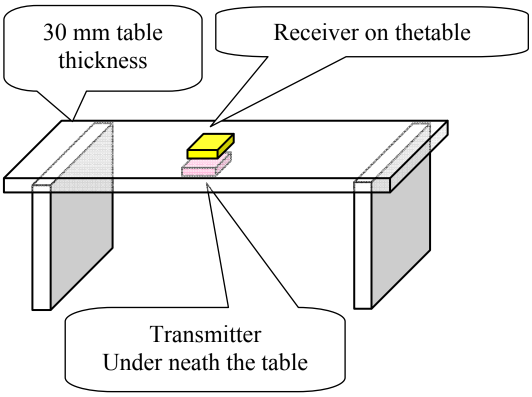
3.2. Low System Losses

The losses in the system compose of losses in the inductor (inner and outer), losses in the capacitors and losses in the DC conversion components. All of those effects sum up and the energy is converted into heat, which results in a lower efficiency. The main contribution of the losses are those of the inductors, the transmitter capacitor is the second large contribution of losses. The losses of the inductors are contributions of the ferrite material and of the wire windings. The primary losses of the ferrite are the hysteresis-, eddy current- and magnetic creep – losses, the losses of the wire windings are resistive losses and eddy current losses due to the skin- and the proximity effects [9-10]. The proper selection of the ferrite material and the optimal construction of the wire winding is essential to reduce the losses and thus to reach an optimum of efficiency [11-12].

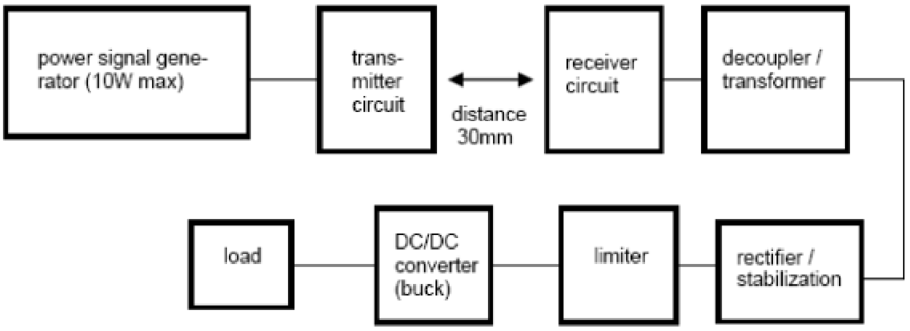
3.3. Resonance Coupling Effect

In our system the resonance coupling effect is based on the evanescent wave coupling which provides advantages for the wireless transmission like almost no stray field to achieve a high efficiency, to fulfill EMF/EMC requirements and to achieve a higher distance with high efficiency compared to other mechanisms. In the previous work of André Kursabout wireless power transfer via strongly coupled magnetic resonances [1], [2], [13] and [14], using the set-up of the resonance coupling of two coils, investigations show thatthe air coils must be large. Efficiency in the power transfer rapidly decreases with increasing distance, it is necessary to use large coils in order to achieve longer coil distances. This is the reason why in the experiments in [1] and [15] the coils have large radia of about 30 cm. Furthermore the receiving coil is very likely to influence its resonance by the load, the coupling effects rises with increasing operation frequency and to transmit the maximum power it requires the optimized matching impedance of all stages.

The selected operating frequency affects the size and weight of the system as well as the efficiency. At a frequency of 13.560 MHz the coupling effects, the skin effect and thus the losses in the components are higher than at 6.78 MHz.Especially ferrite material with the necessary magneical parameters are not available (refer to 3.4.1). Therefore according to Table 1 the operating frequency is chosen to 6.78 MHz. Figure 3 shows the principle system set-up for the transmitter and the receiver. The system itself composes of two main parts: Transmitter and receiver, shown in figure 3.



3(a). Example of transmitter and receiver set up



3(b). Block diagram of the system

Figure 3. Transmitter and receiver system set up and block diagram

The transmitter, with a resonance circuit designed for 6.78 MHz is supplied by a power signal generator with a maximum output power of 15 W. The receiver module consists of a receiver circuit where the resonance circuit operates also at 6.78 MHz, a rectifier/stabilization to convert the RF voltage into a DC voltage, and to buffer the energy for absorbing current dips, using a capacitor stabilization, a limiter to protect the following circuitry from over voltage, a DC/DC buck converter which provides a regulated output voltage in the range between 5 V and 24 V and the load, which is here a 4.7 Ohm resistor.

3.4. Transmitter Circuit

3.4.1. Selection of Ferrite Material

It is essential to use a proper ferrite material for the coils and not an air coil to achieve a high efficiency. A prototype of a wireless power transfer system is built in [16]. Thecontribution of the energy in the resonance system must be primarily magnetic. This is achieved by a high inductance and a low capacitance in both resonance circuits.The ferrite characteristics give the advantage of reducing the circuit in size and increasing the efficiency because of a field concentration and a proper adaption to the field impedance. The ferrite material used here has its resistive part of the complex permeability above 8MHz and thus keeps the losses low. The ferrite material, shown in figure 4, is selected in such a manner that at the operating frequency the imaginary component of the complex series permeability (μ_s'') is almost zero what reduces the losses inside the ferrite to a minimum [10].

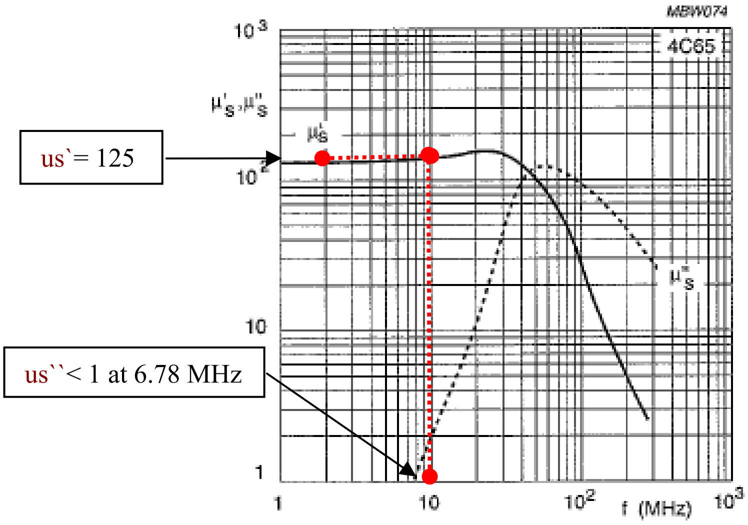


Figure 4. Ferrite characteristic: Complex permeability as a function of frequenc

The complex permeability represents the “magnetic behavior” of the ferrite material and has two contributions, the reactive portion (μ_s') which represents the inductance shown in equation [1] and the resistive portion (μ_s'') which represents the losses shown in equation [2]. The initial permeability of the used ferrite material is 125 as shown in the diagram [11]. For low loss also the capacitive losses between the windings must be kept low, the main energy must be converted within the inductors to the magnetic field. A special winding concept with litz wires has been used.

With a ferrite core the losses in terms of a resistive component add and the simplified diagram, without parasitic effects, is:

$$L_s = L_o \cdot \mu_s' \tag{1}$$

$$R_s = (\omega L) \cdot \mu_s'' \tag{2}$$

Then, the total impedance is

$$Z - (j\omega L) \cdot (\mu_s' - \mu_s'') \tag{3}$$

The absorption factor can be defined as

$$\tan\delta = \frac{R_s}{\omega L_s} = \frac{(\mu_s'')}{(\mu_s')} \tag{4}$$

The ferrite components are shown in figure 5.

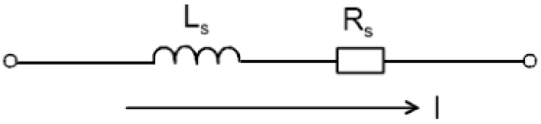


Figure 5. Ferrite core loss components

In case of an alternating magnetization of the ferrite the flux density B is not in phase with the magnetic field produced. In case of “small” magnetization the angleδbetween the resulting magnetization and the flux density represents the loss angle shown in equation [1] and Figure 6.

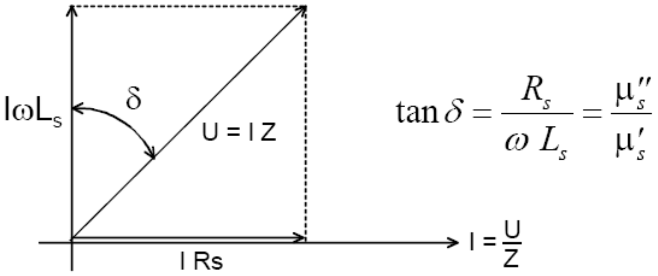


Figure 6. Ferrite core loss parameters

The smaller the angle the higher the performance, the “quality” of the material [17]. In practice the over-all loss angle of the inductance is a combination of the contribution of the ferrite and the coil. In case of larger magnetization the primary losses of the ferrite are the hysteresis, eddy current and magnetic creep losses. The high specific resistance of material, which is NiZn-ferrite shown in Table 2, is required to reduce the eddy currents losses.

Table 1. Specific resistance of selected materials

Composition	Resistance at T = 25°C
MnZn-Ferrite	0.1-10 Ωm
NiZn-Ferrite	10^5-10^6Ωm

3.4.2.The Wire Material at the Transmitter Inductance

Current takes the path of lowest inductance which is also the path of smallest loop area. This results in lower energy being stored in the magnetic field. So current will be concentrated along surfaces that it can be closer to the currents in the return path. At high frequencies, current does not flow evenly throughout the entire cross-section of the conductor but is more concentrated at the surface. The higher the frequency, the more the current is concentrated on the surface. This results in higher I^2*R losses and thus energy loss at higher frequencies. The current density varies exponentially as a function of depth from the surface of the wire. However, it is helpful to think in terms of a skin depth. Skin depth is defined as the distance below the surface where the current density has fallen to 1/e or 37% of its value at the surface [9]. The skin depth at 6.78 MHz is for a copper wire calculated expressed in equation (5)

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \delta_0}} \tag{5}$$

$$\delta_0 = 1.05\ \Omega/\mathrm{m}$$

$$\mu_0 = 4\pi \cdot 10^{-7}\ \mathrm{H/m}$$

$$\delta_{cu} = 5.82 \cdot 10^{7}\ \Omega/\mathrm{m}$$

$$\delta = \sqrt{\frac{2}{2\pi \cdot 6.78 \cdot 10^{6} \cdot 4\pi \cdot 10^{-7} \cdot\ 5.82 \cdot 10^{7} \cdot 1.05}} = 24.7\,\mu\mathrm{m}$$

This shows possible high losses due to the skin effect and in too high current density. The current density is the ratio of current intensity to the area, perpendicular to current direction, into which the current is flowing to. But this is due to the skin effect only in a small circle around the conductor.

Eddy current losses in the windings cause a main contribution of the losses. They are depending on following parameters in equation [6], whereas the material and the field must be uniform and the skin effect may here not be considered [22]:

$$P = \frac{\pi^2 B_p^2 d^2 f^2}{6kpD} \tag{6}$$

P is the power lost per unit mass (W/kg),
Bp is the peak magnetic field (T),
d is the diameter of the wire (m),
f is the frequency (Hz),
k is a constant equal to 1 for a thin sheet and 2 for a thin wire,
ρ is the resistivity of the material (Ω m), and
D is the density of the material (kg/m3).

This equation is valid only under the so-called quasi-static conditions, where the frequency of magnetisation does not result in the skin effect what means the electromagnetic wave fully penetrates the material. But it shows clearly the dependency of the wire parameters like thickness (d) and material constants (ρ and D). The other parameters are system depending and can not be varied.

Another important parameter for the resonance system is the self-resonant frequency (SRF) of the coil as the parallel capacitance of the resonance circuit is quite small. The self- resonant frequency depends on the parasitic capacitance of the inductor and to achieve a highself-resonant frequency the parasitic winding capacitances must be low. For that it is necessary to use the suitable copper wire size and a proper layout [18]. The variation of the coil may change [10] with the number of turns, twisting factor, amount of litz wires, density of turn layout, the impedance matching to power amplifier and to the system receiver and the magnetic field contribution of the efficiency.

3.4.3. Investigation of the Transmitter and Receiver with Resonance Effect

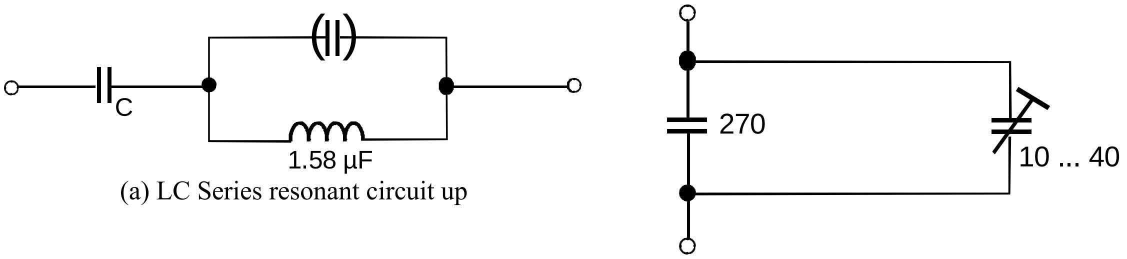
3.4.3.1. Transmitter Circuit

A series resonance circuit is selected; this provides in comparison to the parallel resonance a more stable behavior of the power amplifier. The transmitter coil has 5 turns which gives an inductance of 1.58 µH a frequency of 6.78 MHz. The series resonant capacitance, shown in Figure 7a, can be calculated from Equation (7). The practical capacitance can be simplified as illustrated in Figure 7b. The resonant transmitter circuit is composed of the inductor and the variable series capacitor as shown in Figure 7c.

$$X_L = X_C \tag{7}$$

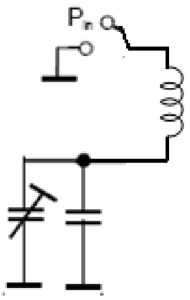
$$\omega L = \frac{1}{\omega C}$$

$$C = \frac{1}{L\omega^2} = \frac{1}{1.58\times10^{-6}\cdot\left(2\pi\cdot6.78\times10^{6}\right)^2} \approx 349\,pF$$



(a) LC Series resonant circuit up

(b) Practical capacitance



(c) Inductor and variable series capacitors

Figure 7. Transmitter resonance circuit

3.4.3.2. Receiver Circuit

The receiver resonance circuit has to supply a nonlinear load like the rectifier bridge, bulk capacitors and the DC/DC converter. This may influence the resonance behavior therefore a parallel resonance circuit has been chosen.Furthermore the adaptation to the near field magnetic impedance has to match. The parallel resonance circuit used for the receiver is shown in Figure 8.

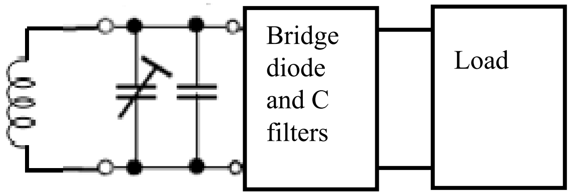
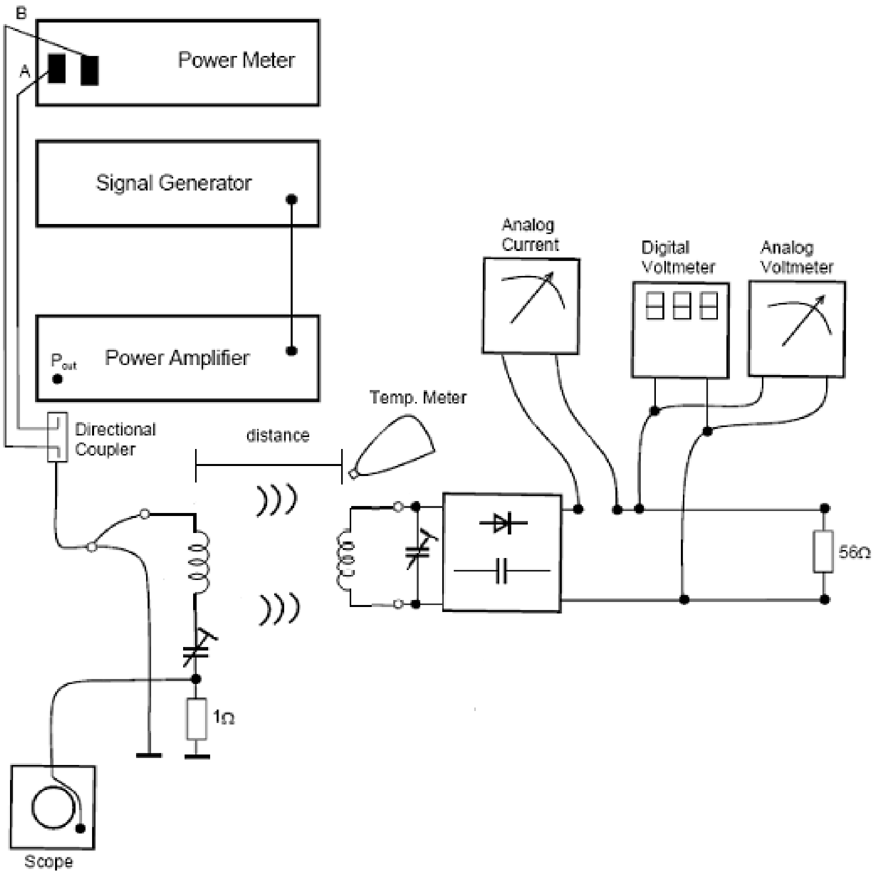


Figure 8. Receiver resonance circuit

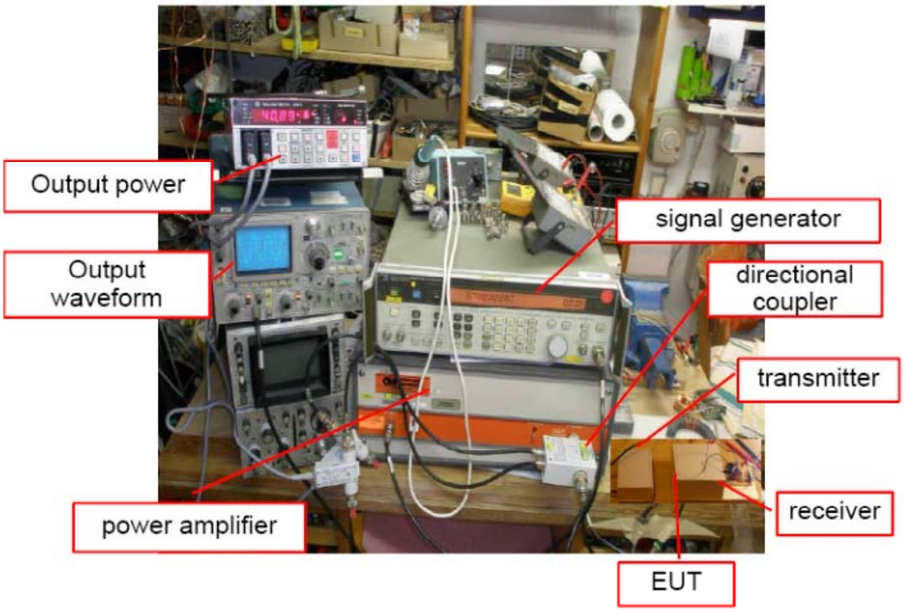
The parameter of the inductance and the capacitance can be calculated based on the same resonant frequency, 6.78 MHz. With an additional matching transformer at the receiver side, the winding turn ratio between the receiver resonance circuit and the AC/DC stage the voltage level for any nonlinear load can be adjusted.

4. WIRELESS POWER TRANSMISSION PERFORMANCE

The performance of wireless power transmission can be considered by parameters like efficiency, coil distance and transmission power density. The system can be driven with a power up to 200 W, limited by the inductor and the capacitor. The wireless power transmission system for testing has been set-up as shown in Figure 9a and 9b.



9(a).Test set-up diagram



9(b).Test set-up measuring system

Figure 9. Test set-up for the precise measurements of the system efficiency

For the precise measurements of the efficiency a calibrated millivolt meter with precision insertion units has been used as shown in Figure 10.

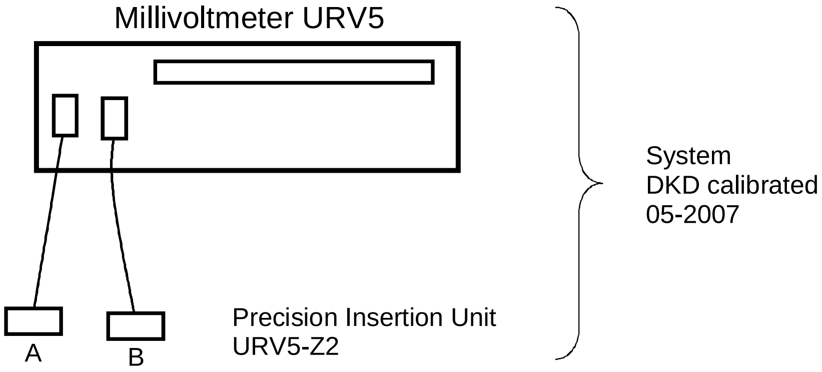


Figure 10. Precision power meter (millivolt meter with insertion units)

4.1. EMC and EMF Considerations

As shown with a high sensitivity sensor which detects fields in the range of 0,05uT it can be shown that the field of the inductance is limited to the area between transmitter and receiver and only susceptible to receivers at the same resonance frequency and this outside of the beam has no considerable biological effect. Figure 11 illustrates the set-up.

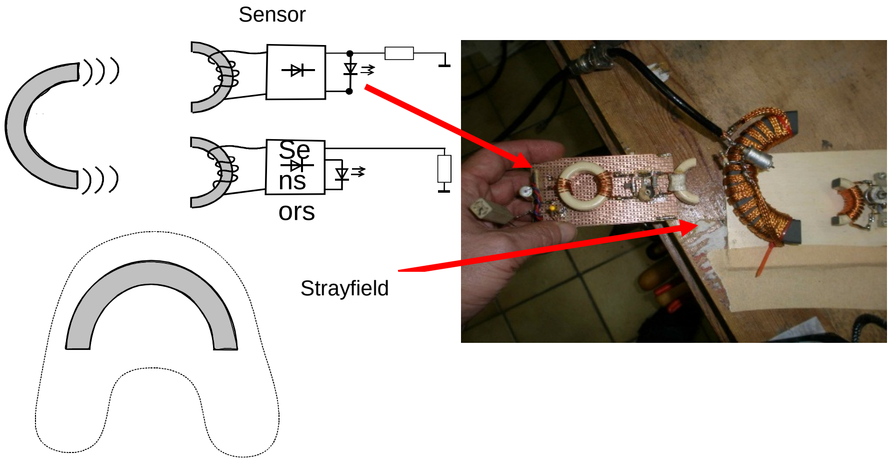


Figure 11. Set up of radiation measurement with a high sensitivity sensor

4.2. Experimental Results

The efficiency of the wireless power transmission can be measured with a gap of 42 mm as set-up in figure 9. The centered diameter of the core is 42 mm. Signals coupled by a 40 dB directional couplerat the oscilloscope are shown in Figure 12.

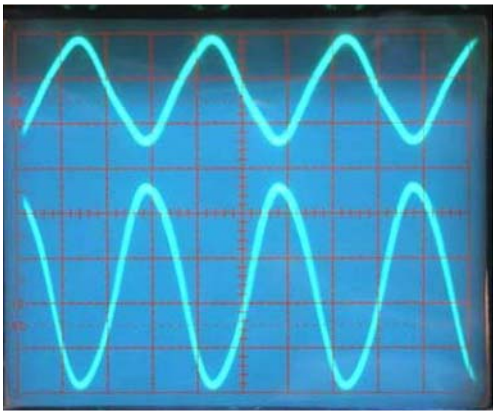


Figure 12. Signals at directional coupler,
- Upper trace is output B (reflection from load), 50 mV/div at 50 Ohm (130 mVss)
- Lower trace is output A (Signal from PA), 200 mV/div at 50 Ohm (920 mVss)
- Horizontal: 50 ns/div (perform operating frequency at 6.78 MHz)

The upper trace is the reflected voltage from load at output B about 130 mV, while the lower trace is the signal from preamplifier at output B about 920 mV at operating frequency 6.78 MHz. The input of the bridge rectifier results 10 Vss shown in Figure 13.

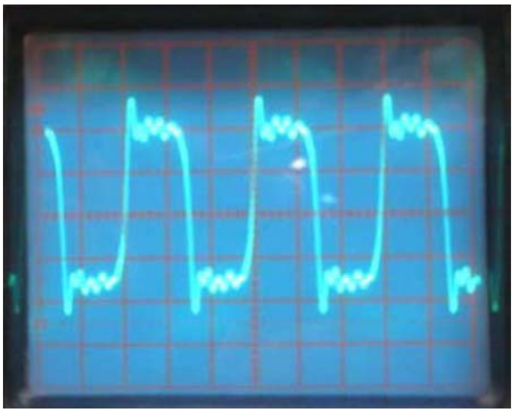


Figure 13. Input of the bridge rectifier

- 2V/div (10 Vss)
- Horizontal: 50 ns/div

The measured result and the corresponding signals are shown and calculated as follows:

4.2.1. Result at a Distance of 50 mm:

Warm up: >1h ϑ: (32-35)°C core, (40-43)°C coil, V_{DC}: 26.5 V

$P_{in}= P_{ow} A + K = 17$ W

$P_{out}= (V_{DC})^2 / R_{load} = (26.5\ )^2 / 56 = 12.55$ W

$$\eta_{\%} = \frac{P_{out}}{P_{in}} \cdot 100 = \frac{12.55}{17} \cdot 100 \quad \approx 73.82\ \%$$

4.2.1. Result at a Distance of 42 mm:

Removed Transmitter sensor (1 Ω resistor) for optimized matching and reduce all losses.

ϑ: after warm up (> 1h): core: 29°C, coil: 32°C, V_{DC}: 22.5 V

P_{in}: 8.1 W + K = 10.2 W

$$\eta_{\%} = \frac{(22.5)^2}{10.2\ x 56} \cdot 100 \quad \approx 88.6\ \%$$

The measured power at the 56 Ohm load is 9.04 W where the voltage across the load is 22.5 V. The transmitted power measured via the directional coupler gives the power P_{in}: 8.1 W + K = 10.2 W. The power efficiency is 88.6%. The temperature of the transmitting core and coil is stable at at 32°C after run for 1 hour.

4.3. Possible Transmitted Distance

The operating frequency is 6.78 MHz, then, the wave length is 44.24 m. The non-radiative near field distance from the source to the receiver is the wave length divided by 2*pi. Thus, the possible wireless power can be transmitted up to 44.24/2*pi = 7.04 m. The simulation is shown in Figure 14, the magnetic flux densityin the diffraction range at a distance r is proportional to $1/r^2$. The trace of magnetic flux density over the ratio of distance to the wave length in Figure 14 shows that it is possible to apply the wireless power transmission approximately up to 0.016 of the ratio of distance to the wave length.

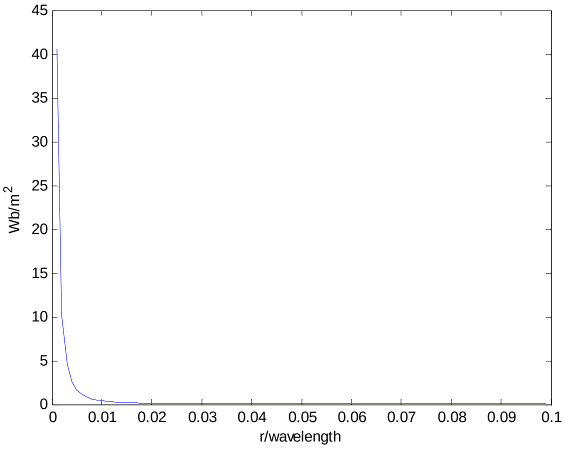


Figure 14. Simulation of magnetic flux density with the ratio of distance to the wave length

4.4. Transmitted Power Density

The transmitted power density is defined as the ratio of maximum transmitted power per active area of the inductor core. At a transmitted powerof 80 W with the cross section of the ferrite core [11] like shown in Figure 15 which is 15.3 x (102.4-65.5) = 564.57 mm^2 or 5.65 cm^2 the maximum transmitted power density achieved is 0.14 W/mm^{2}which is 140 kW/m^2! For comparison, the power densitiy of the sun light is 1,37kW/m^2, the power densitiy of Uran is 650 kW/m^2.

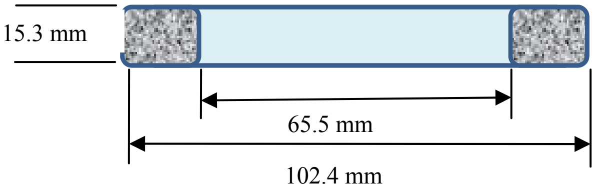


Figure 15. Cross section area of the transmitting and receiving core

4.5. Applications

Figure 16 shows the transmission of power through a glass block with a thickness 8 cm.

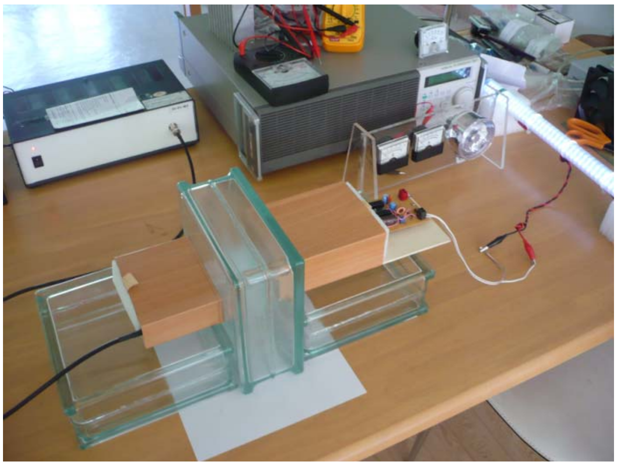


Figure 16. Transmitting the power through the block glass with the thickness 8 cm

The application in Figure 17 shows the supply of a LED lamp at a distance of 10 cm.

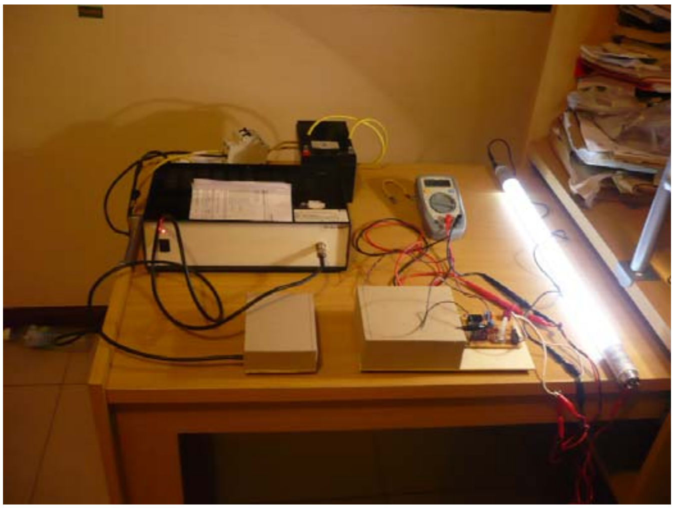


Figure 17. Transmitting the power through the 10 cm air gap

A wireless power transmission through a 9 cm cement wall is demonstrated in Figure 18.

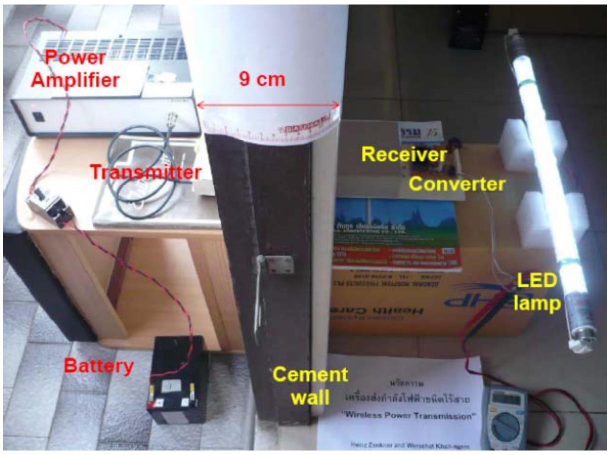


Figure 18. Transmitting the power through the cement wall with 9 cm thick

A further application may also befor example a storage energy charging system for vehicles. Applications of other researchers focus on areas such as: Wireless power transmission with multi receivers in power supply system [16], wireless power and data link [20], wireless charging systems [21] or Wireless Power Standardization for supply and charging of small appliance [22]. Each of the applications has its individual advantage but none of them can combine the key features which are small size, proper distance between transmitter and receiver, EMC consideration and high efficiency. The applications work in the range from 100 kHz up to 27 MHz so many not in the ISM band, some reach an efficiency up to 90% but work at low distance and on magnetic coupling basis.

5. CONCLUSION

Compared to more theoretical related papers, it is shown in this work that with defined parameters and restrictions for practical use as a precondition, it is possible to achieve a result which can be used already for industrial design. The work shows that it is possible to transmit high power via the air keeping still a high efficiency, a low weight, a small size and also EMC/EMF restrictions. The circuit enables a power transmission under conditions which make the receiver safely in use as no cables or batteries need to be used. Thus there is a wide range of application possible like in medical appliance or appliance for chemical industy where special precautions must be taken.

The parameters of wireless power performance are the distance between transmitter and receiver, the transmitting frequency and the system impedances. The key for the principle is the resonance effect together with a high performance ferrite inductor which allows fulfilling the preconditions like EMC/EMF and efficiency. The various load conditions normally affect the matching impedances and thus they have to be decoupled from the transmission system here done with implementing an additional matching transformer. The efficiency is significantly depending on the transmitter resonance circuit where the highest power of the whole system is handled. The components used here have to be optimized regarding low loss and small size. The maximum efficiency of 88.6% is achieved at a gap of 42 mm with 9 W output power. This output power can be applied to any appliance having any load impedance. The maximum transmitted power density achieved is0.14 W/mm^2 which is 140kW/m^2! The component and material selection and design are essential to reach a high performance transmission. The further progress in this work is focused on how to maintain the high efficiency wireless power transmission at various distances and how to keep the high efficiency at longer distance.

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