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1 SUMMARY 2
2 INTRODUCTION 2
3 TECHNOLOGY AND STATE-OF-THE-ART 3

3.1 Overview standards and regulations 3
3.2 Current possibilities and usage of the technology 4
3.3 Definition of Test Cases 5

4 SYSTEM-LEVEL MODEL OF THE CHARGING SYSTEM 6
5 SURVEY OF PACKAGING AND SYSTEM-INTEGRATION CONCEPTS 8
6 COILS IN SUBSTRATE: MODELING 9

6.1 Patent Review 9
6.2 Development of Modeling Methodology 15
6.3 Comparison of Coil Performance in Different Technologies 18
6.4 Impact of Process Tolerances 18
6.5 Stacked Coils 19
6.6 Staggered Coils - Homogeneity of the magnetic field 22

7 COILS IN SUBSTRATE: REALIZATION 26

7.1 Design of Test Samples 26
7.2 Measurement of Test Samples 27
7.3 Comparison Measurement and Model 29

8 FERRITE IN SUBSTRATE: MODELING 29

8.1 Literature Review 29
8.2 Impact of Ferrites on Coil Performance 33
8.3 Modelling Methodology 35

9 FERRITE IN SUBSTRATES: REALIZATION 36

9.1 Design of Ferrite Coils 36
9.2 Fabrication of Test Samples 37

10 DRIVER AND RECEIVER MODELLING 37
11 DRIVER AND RECEIVER REALIZATION 38
12 DISSEMINATION OF KNOWLEDGE 38
13 LITERATURE 39
14 DISTRIBUTION OF TASKS 39

1 Summary

The project Wipos was dealing with the realization of wireless charging modules. Both the driver electronics as well as the charging coils respectively in the transmitter and receiver were modelled. After an assessment of the technology and state-of-the-art the required inductance was determined. The coils were analyzed and modelled with and without ferrite. Test samples were designed and measured for the validation. The results were demonstrated on a test case, to demonstrate the design flow.

The research objectives have been partly accomplished (Das Forschungsziel wurde zum Teil erreicht).

2 Introduction

With the increasing number of mobile devices the power supply is becoming an issue. In the mobile appliances the required energy is stored in a battery with limited capacity that has to be recharged regularly. Despite the use of energy saving measures the energy consumption is increasing due to the increased functionality. To extend the running time of mobile devices the battery would have to be increased which in turn implies more weight and size.

The energy for recharging the batteries is typically supplied by cables that connect to charging adapters. They are electrically connected with connectors. Depending on the form factor and power requirements a vast variety of connectors are available. It is common practice to carry a number of chargers which is very inconvenient. For some applications, e.g. in areas that are subject to explosion hazards, connectors may not be allowed.

An alternative is the use of electromagnetic fields to supply the power for recharging the batteries. The principle is well known from, e.g. from electric tooth brushes. An inductor in the base station generates a magnetic field that induces the charging currents in the secondary coil in the handle of the tooth brush. Other examples include the use of electromagnetic waves in the operation of RFID systems. The operation principle of charging based on electromagnetic fields is often called *wireless charging*.

However the use of wireless charging systems implies a redesign of the energy supply sub-system, including the energy transmitting base-station that converts the mains power to the required electromagnetic fields, the design and realization of the wireless transmission system to the receiver electronics. There are a large number of design choices to be made which involves a potentially long development phase. This implies high cost, especially for smaller companies with limited staff in their research teams.

The goal of the project is to support the design of wireless charging systems in order to make it easier to evaluate and adopt wireless charging in the design mobile systems. This is done by supplying design manuals and tools based on comprehensive research on the design of the components of a wireless charging system.

As wireless charging is an alternative technology to cable based charging the requirements are similar: the system should be able to charge the battery of a mobile appliance with minimal assistance by the end user. The duration of the charging process should be as small as possible but is typically several hours similar to cable based charging. In order to save on the cost and reduce wasting energy the efficiency of the charging process should be as high as possible. And depending on the application safety and electromagnetic interference regulations for the operation of electronic systems have to be respected. Typically there is only a short distance (some cm) between the charging station and the mobile appliance and while the charging time should be as short as possible the power transmitted is small (some Watt). As many batteries are sensitive to the charging conditions (e.g. overcharging, charging current and voltage) the charging current has to monitored and controlled. This requires a control electronics in the transmitter and a data transmission from the receiver back to the transmitter.

Politics and some mobile device manufacturers in the European Union have responded to this problem with a memorandum of understanding that makes the use of Micro-USB connectors for data-enabled mobile devices mandatory.

3 Technology and State-of-the-Art

Generally speaking a wireless charging system is made up of a base station that generates the electromagnetic fields from a mains supply and one or more receiving systems that are able to pick up the fields and convert it back to a charging current and voltage for the power supply in the mobile devices. The electromagnetic fields are transmitted via antennas in the transmitter and receiver. In order to achieve a high efficiency the antennas as well as the drive current have to be adapted to the operating conditions. The conversion of the mains power to the driving current and the received current to the charging current is done by driver electronics in the transmitter and receiver, respectively.

There is already a vast amount of scientific literature and information available that is concerned with the wireless transmission of electromagnetic fields and the necessary components and driver circuits. The following sections give an overview on the industry standards that are concerned with wireless charging as well as on the design of commercially available charging systems and the scientific literature.

3.1 Overview standards and regulations

There are three major alliances on the wireless power market, the power matters alliance (PMA), the alliance for wireless power (A4WP standard), and the wireless power consortium (WPC) with the Qi-standard. Now (first quarter of 2015) PMA and A4WP have joined forces and formed a group called Rezense.

There are already more than 150 members in the WPC and more than 300 products include wireless charging functionality. The numbers are steadily increasing (cf. figure 1).

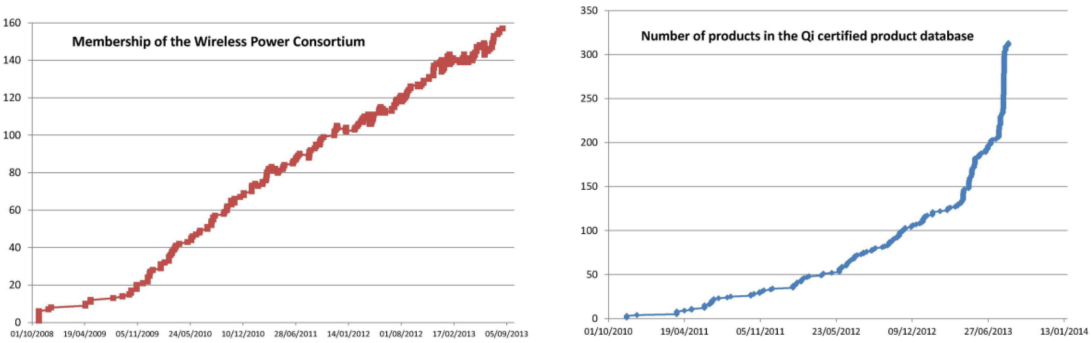


Figure 1 Membership (left) and number of Qi certified products (right)

FhG IZM and DraMCo are inclined towards the Qi standard advocated by the Wireless Power Consortium [1], but the work accomplished in this project is largely independent of this choice.

The Wireless Power Consortium are releasing standard documents that give details about the electrical specifications. Some relevant specifications of the Qi standard are [1]:

- Contactless power transfer based on induction between coupled coils.
- Transfer of approx. 5 W of power with a secondary coil with ~400 mm radius
- Frequencies in the 100…250 kHz range.
- Two methods of placing the mobile device on the surface of the base station:
    - Guided positioning on fixed position(s) of the surface.

- Free Positioning on any location of that surface.
- A simple communications protocol where secondary takes control of the power transfer.

In addition to the technical specifications for the Qi standard there are safety regulations that are concerned with the operation of the wireless charging units. Apart from electrical safety there are limits on the maximum emitted field strength. An example is the ICNIRP standard for magnetic fields.

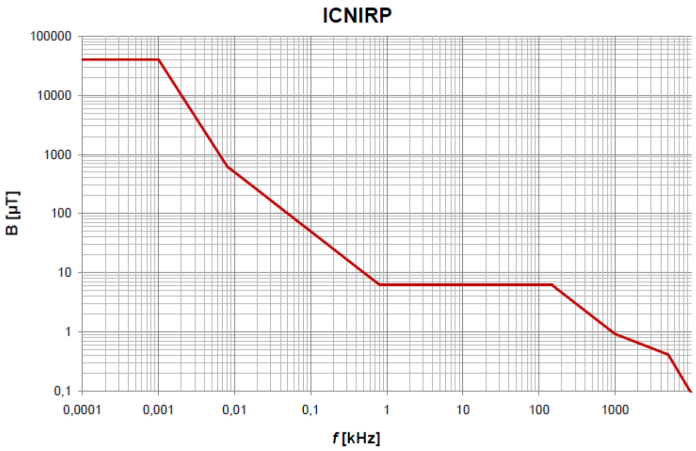


Figure 2 Limits on magnetic field emissions according to ICNIRP standard

Stray magnetic fields have to be controlled to avoid excessive exposure (≤ 6μT at 100 kHz)

3.2 Current possibilities and usage of the technology

The principle of transferring power by means of electric or magnetic fields have been applied before and products based on this are already available.

Figure 3 Applications with wireless charging function: electric toothbrush (left), torch (center), smart watch (right)

A possible classification can be done based on the quantity of the electromagnetic field that is being used for the power transfer. Capacitive power transfer uses the electric field while inductive power transfer relies on the magnetic field. Figure 4 shows available modules for capacitive and inductive charging. The operating frequencies are in the kHz range and the charging distance is typically limited to some cm.

As the operating frequency is increased the coupling between the electric and magnetic field is becoming more important. If the wavelength of the frequency used for charging is comparable to the dimensions of the antenna that generates the fields, radiation of electromagnetic waves can be excited efficiently. This allows for transmission of electrical power by electromagnetic waves.

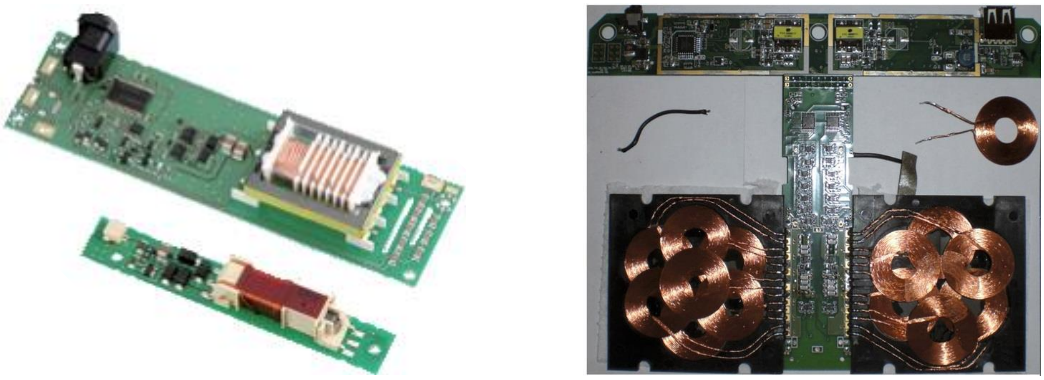


Figure 4 Wireless charging modules, left: capacitive (Murata), right: inductive (Energizer)

Two typical scenarios complying with the Qi standard are described below. They have served as starting points and benchmarks for the systems to be developed in the project.

3.3 Definition of Test Cases

In order to test the results of the project two test cases were examined more closely. The test cases suggestions of the project were approved by the project User Committee. The first test case is a wireless charging unit is built into a wireless computer mouse to replace two AA batteries. The charging unit in the mouse contains the receiver coil, the driver electronics and a super capacitor for energy storage.

Figure 5 Wireless mouse test case with receiver coil using different technologies, left: Litz wire, right: PCB

For the second test case the components of a wireless battery charger were built. For the initial prototype only commercially available Litz wire coils were used. All coils were commercially available except the receiver coil for the wireless mouse which had to fit into the rectangular battery compartment of the mouse casing. The receiver mouse coil was hand wound using Litz wire on a ferrite slab.

Figure 6 Initial Litz wire coils for wireless mouse charger, left: transmitter, right: receiver

The receiver coil is a Würth® receiver litz wire coil placed on a ferrite plate. For the transmitter coil a standard Qi-transmitter coil (Elec&Eltek) of 10 turns (litz wire) without magnet is used.

Figure 7 Battery charger, transmitter coil (left) and receiver coil (right)

Litz wire coils are typically, though not exclusively, used in present applications. One of the major goals of the project was to replace these coils by coils manufactured by PCB technology, keeping the dimensions fixed.

4 System-Level Model of the Charging System

The wireless charging system can be broken down into a number of sub-systems following the blocl level diagram in figure 8. The electrical power is supplied by a power supply (either DC, e.g from a battery or AC from mains connection). The current of the power source is transformed into the driving current for the transmitter inductor of the charging transformer to achieve a high transfer efficiency. The magnetic link of the transformer transmits the power by means of the magnetic field that is generated in the primary side inductor. In the receiver coil the magnetic field is again converted to an AC current. As most mobile devise require a DC supply voltage the AC current is rectified and its voltage regulated. The Qi-protocol specifies also an indication of the charging status from the load to the transmitter controller so that the charging current and voltage can be optimized.

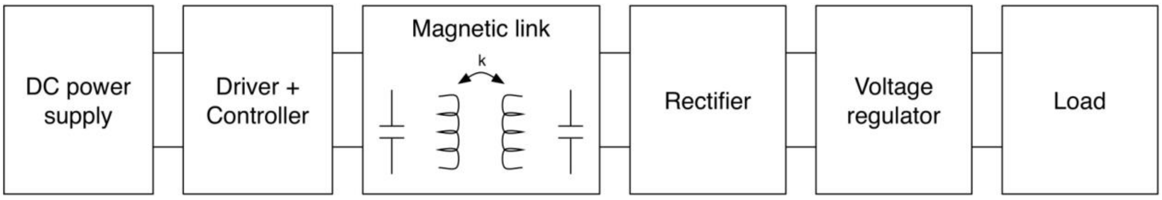


Figure 8 System-Level model of wireless charging system

In order to analyse the power transfer mathematically the magnetic link is modelled as a transformer.

$$v_1(t) = L_1 \cdot \frac{di_1(t)}{dt} + M \cdot \frac{di_2(t)}{dt}$$

With $v_1(t)$ the voltage at coil 1, L_1 the self-inductance and $M_{12} = M_{21}$ the mutual inductance depending on the number of windings, shape, position and the material properties (μ, ρ) of the coils. There are two operating modes possible – the non-resonant and the resonant case. In the non-resonant case the electrical equivalent circuit of figure 9 can be constructed from the general transformer equation.

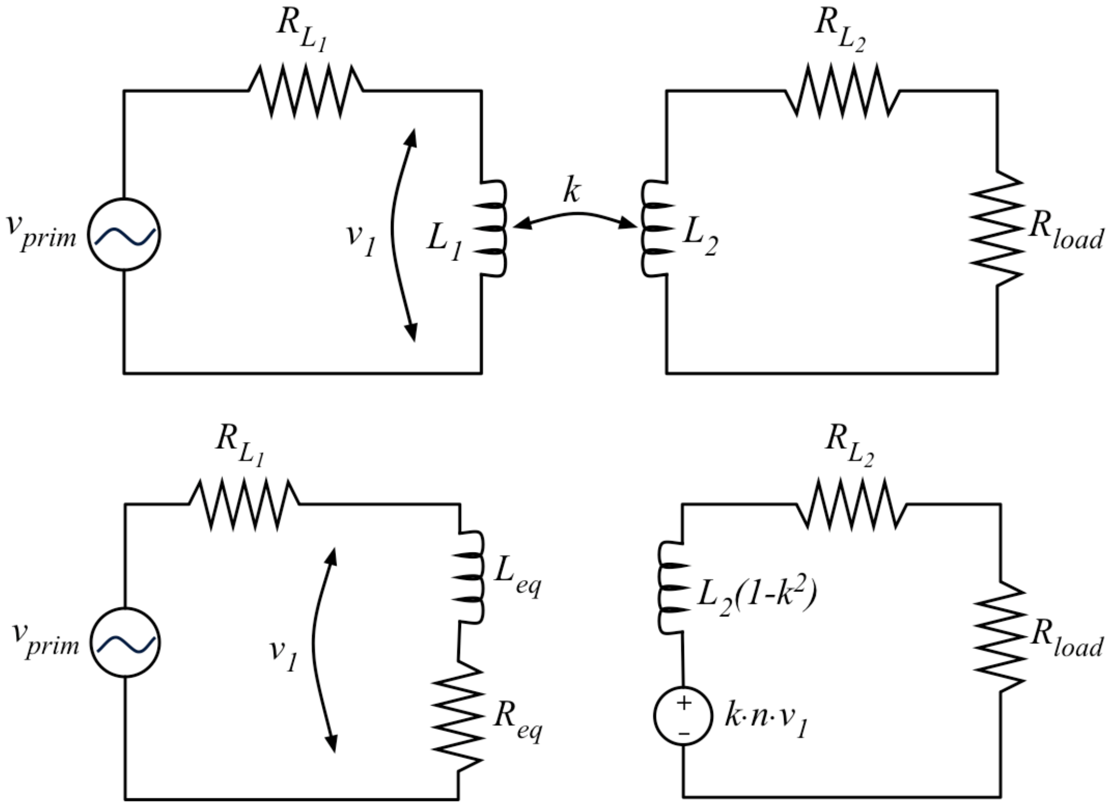


Figure 9 Equivalent circuit of non-resonant magnetic link

Calculating the link efficiency based on the equivalent circuit for this operating mode one arrives at figure 10

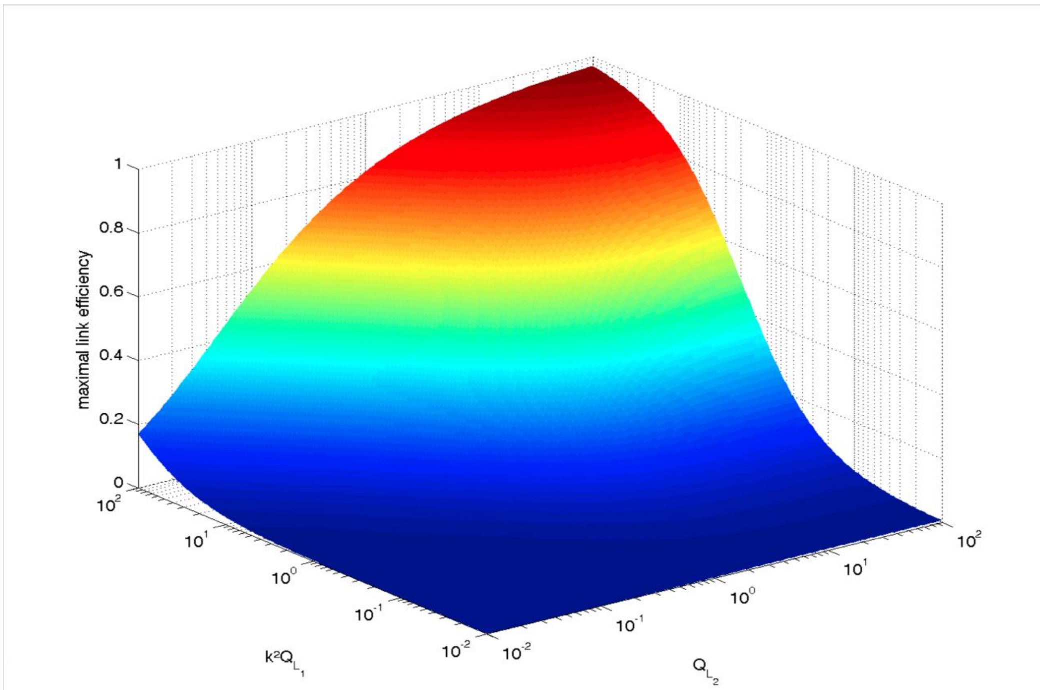


Figure 10 Link efficiency vs. coil quality factor

In case of the resonant magnetic link the transfer efficiency is increased when as can be seen in figure 11.

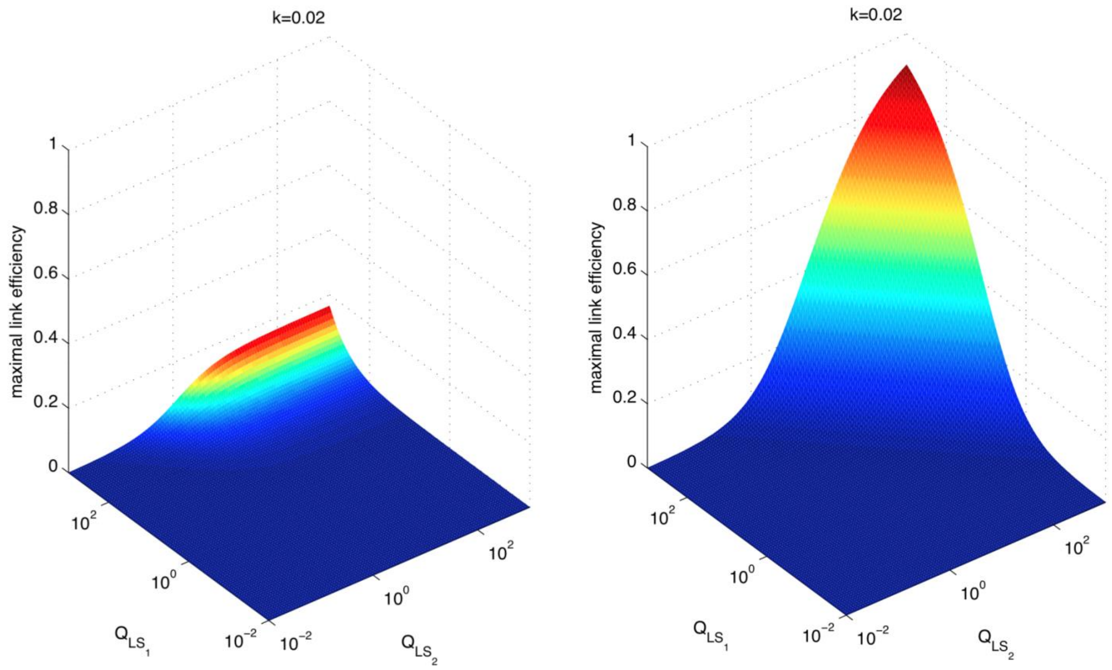


Figure 11 Comparison of Maximum link efficiency for non-resonant and resonant magnetic link

While a series resonance behaviour of the secondary LC tank behaves as a current source for low load resistance (<<ω L_2) a parallel resonance can be modelled as a voltage source for high load resistance (>>ω L_2)

5 Survey of Packaging and System-Integration Concepts

Commercially available charging stations typically use litz wire coils, which are placed on top of a ferrite. The insulation is provided by a plastic foil. The following pictures show some examples compatible with the Qi standard:

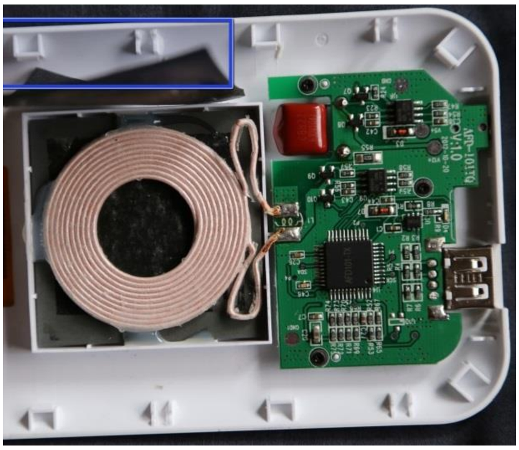


Figure 12 Qi compatible charging station

The charging station in figure 12 has a single Lutz wire coil on a ferrite slab. The coil is connected to a PCB containing the charging and control electronics. In the mobile phone charger (figure 13) there are three coils arranged to increase the charging area. Coils are again mounted on a ferrite sheet. The charging electronics is situated underneath the coils with a metal shield between the coils and the PCB to prevent electromagnetic interference.

The construction of a coil array similar to the one used in the charger is shown in figure 14. The Litz wire coils and a thin insulating layer of PET are glued to the ferrite sheet with adhesive tape. The bottom coils have an inductance of approx. 12.5 µH each while the top inductance is only 11.5 µH due to the effect of the mutual inductance. The quality (Q) factor of the coils is approx. 70.

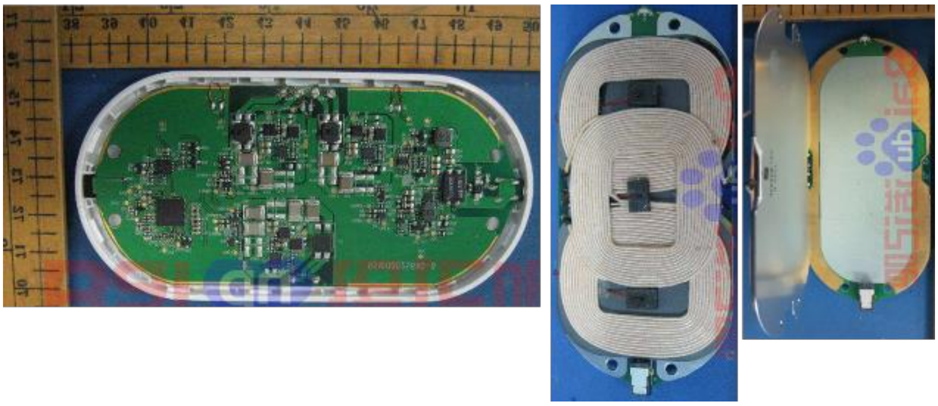


Figure 13 Nokia DT 900 Charger

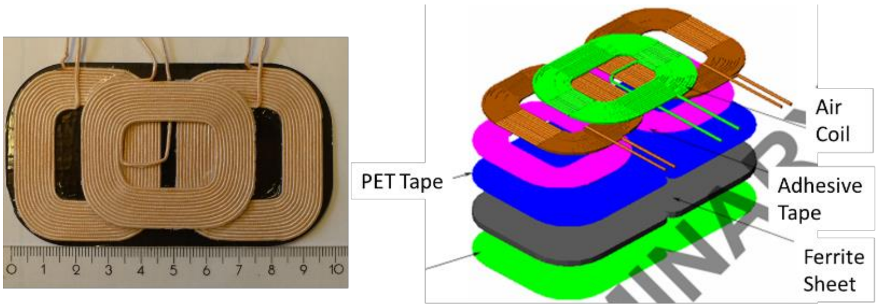


Figure 14 TDK planar coil array, L=11.5, 12.5 µH, Q value ≅ 70

6 Coils in Substrate: Modeling

This section contains information on the modelling of inductors with magnetic core so called air core inductors.

6.1 Patent Review

In the following, the results of a selection of applicable patents are presented:

Wireless power transmitting apparatus and method thereof (LG Innotek Co., Ltd.), EP2642628 A1, US 20130241304 A1

Disclosed are a wireless power transmitting apparatus and a method thereof. The wireless power transmitting apparatus wirelessly transmits power to a wireless power receiving apparatus. The wireless power transmitting apparatus detects a wireless power transmission state between the wireless power transmitting apparatus and the wireless power receiving apparatus, and generates a control signal to control transmit power based on the detected wireless power transmission state. The wireless power transmitting apparatus generates the transmit power by using first DC power based on the control signal, and transmits the transmit power to a transmission resonance coil through a transmission induction coil unit based on an electromagnetic induction scheme.

Power System (Accesss Business Group International Llc), • US 20100084918 A1

The present invention provides methods and apparatus for reducing power consumption. One method includes detecting the presence of an object, identifying whether the object is a valid device and restricting power if its not a valid device. Another method includes temporarily applying a low amount of power to the primary unit to detect a load, supplying more power to determine if its a valid secondary device, and restricting power if its not. An apparatus for reducing power consumption includes two power inputs, where the lower power input powers a sense circuit. A switch selectively decouples the higher power input from the primary subcircuit during detection mode and couples the higher power input to the primary subcircuit during power supply mode.

Wireless power transmitter, wireless power repeater and wireless power transmission method (Lg Innotek Co. Ltd), • WO 2013048004 A1

Disclosed is a wireless power transmitter which wirelessly transmits power through a wireless power repeater to a wireless power receiver using resonance. The wireless power transmitter includes a power supply unit for outputting AC power having a predetermined frequency, a transmission coil for receiving the AC power to generate a time-variable magnetic field, and a transmission resonant coil unit for transmitting power received from the transmission coil coupled with the transmission resonant coil, wherein the wireless power transmitter determines a resonance frequency for a power transmission while controlling a frequency of the AC power output from the power supply unit and a resonance frequency of the transmission resonant coil unit.

Inductive charging system (Plantronics Inc.), US 7211986 B1

An apparatus for inductive charging a battery. The apparatus includes a housing with a lower surface and a charging surface. A rechargeable device with a rechargeable battery may be placed on the charging surface. The apparatus further includes a controller for driving an oscillator, wherein the controller receives power from a power source. A first charger coil and second charger coil are disposed within the housing and are coupled to the oscillator. The first charger coil and second charger coil create a substantially horizontal magnetic field in the volume of space above the charging surface.

Wireless power transmission for electronic devices (Qualcomm Incorporated), • US 20100109443 A1

Exemplary embodiments are directed to wireless power transfer. A wireless power receiver includes a receive antenna for coupling with a transmit antenna of transmitter generating a magnetic near field. The receive antenna receives wireless power from the magnetic near field and includes a resonant tank and a parasitic resonant tank wirelessly coupled to the resonant tank. A wireless power transmitter includes a transmit antenna for coupling with a receive antenna of a receiver. The transmit antenna generates a magnetic near field for transmission of wireless power and includes a resonant tank and a parasitic resonant tank coupled to the resonant tank.

Passive receivers for wireless power transmission (Qualcomm Incorporated), US 8432070 B2

Exemplary embodiments are directed to wireless power transfer. A wireless power transmission receiver includes a receive antenna including a parallel resonator configured to resonate in response to a magnetic near-field and couple wireless power therefrom. The receiver further includes a passive rectifier circuit coupled to the parallel resonator. The passive rectifier circuit is configured to transform a load impedance to the parallel resonator.

Transmitters for wireless power transmission (Qualcomm Incorporated), US 8532724 B2

Exemplary embodiments are directed to wireless power transfer. A wireless power transmitter includes a transmit antenna configured as a resonant tank including a loop inductor and an antenna capacitance. The transmitter further includes an amplifier configured to drive the transmit antenna and a matching circuit operably coupled between the transmit antenna and the amplifier. The transmitter also includes a capacitor integrating the antenna capacitance and a matching circuit capacitance.

Tunable wireless energy transfer systems (Witricity Corporation), US 8643326 B2

Described herein are improved configurations for a wireless power transfer. A power source for driving a resonator includes a switching amplifier. The duty cycle of the switching amplifier may be adjusted as well as optionally inductors and/or capacitors of the circuit to improve the efficiency of power transfer from the power source to the resonators when the parameters of the resonant load change.

System for charging a rechargeable battery of a portable unit in a rack (Ericsson Radio Systems B.V.), US 5367242 A

A system for charging a rechargeable battery of a portable unit in a rack includes a detection circuit which detects the presence of the unit in the rack. The system has circuitry for transferring of energy from a supply circuit of the rack via a charging circuit of the unit to the battery. The transfer circuit is formed by an induction path which comprises a coil of the rack and a coil of the unit. The unit has a transmission circuit which, after placement of the unit in the rack, transmits a message via a wireless path, for example the induction path, to a control circuit of the rack, the control circuit being connected to the supply circuit. If the rack does not receive, or does not satisfactorily receive, a message expected upon placement of the unit in the rack, the control circuit controls the supply circuit so as to make the supply circuit select a higher transfer rate than normal for the purpose of transferring energy to the battery via the induction path. If the rack does receive a valid message, the normal transfer rate is selected unless the supply circuit receives a command to select a different rate. The portable unit may also have a detection circuit by which the unit may detect itself being placed in the rack and is then able to emit the message at its own initiative.

Electric power transmitting device with inductive coupling (Nippon Soken Inc.), US 5070293 A

An electric power transmitting device transmits electric energy from one coil to another coil through an inductive coupling therebetween. One of the coils has an end bent in the axial direction of the coil. When the other coil is to be inserted into said one coil, it can be inserted in not only the axial direction of said one coil, but also a direction transverse to the axial direction through the bent end of the coil. Said one of the coils is typically housed in a holder, and the other coil in the grip of a gun-shaped, hand-held bar-code scanner. When the grip is inserted into a groove defined in the holder, the coils are magnetically coupled to each other, thus providing an inductive coupling. The bar-code scanner can easily be placed on and removed from the holder.

Power Connection Scheme (Apple Computer Inc.), US 5455467 A

A computer that can be electrically coupled to an adapter with wireless inductive connectors. The adapter has a first primary inductive connector that provides power and a second secondary inductive connector that receives digital signals. The computer has a first secondary inductive connector that can receive power and a second primary inductive connector that provides digital signals. The connectors are located within the adapter and computer, so that when the computer is placed adjacent to the adapter, the inductive connectors became electrically coupled.

Inductive power pick-up coils (Boys, Green), US 5528113 A

A loosely coupled inductive power transfer system suitable for transferring power to a mobile conveyer platform or a vehicle has pick-up coils wound on flux concentrator(s). One or more large flat horizontal ferrite cores 607, 608 are used to concentrate the horizontal component of magnetic flux from an extended volume into one or more secondary or pick-up coils 613. Each shock-resistant core comprises an array of many individual strips of ferrite held in close contact. One, more usually two, or perhaps more resonant pick-up windings are wound about each core and each winding has a shorting switch (within 602, 603 . . .) placed across it. A controller 601 connects a controlled output voltage on to an output bus 605, 606 from the best-placed pick-up winding on any one core at any moment, while holding the others in a shorted hence inactive state.

Induction charging apparatus (Kyuchi Hitachi Maxwell, Ltd. Nintendo Co. Ltd.), US 5550452 A

The induction charging apparatus has a power source unit and a device unit which can be detachably coupled to the power source unit. The power source unit has a first casing having one end opened, a primary coil provided in the first casing, an oscillator for supplying an alternating current to the primary coil to generate magnetic fluxes, and a depressible member movably provided and closing the open end of the first casing. The depressible member is movable between a lift position at which the magnetic fluxes are substantially located under the depressible member, and a depressed position at which portions of the magnetic fluxes are substantially located over the depressible member. The device unit has a second casing having one end detachable to the open end of the first casing, a secondary coil provided in the second casing and adjacent to the one end, and rechargeable battery provided in said second casing for receiving power from the secondary coil. When the second casing is attached to the first casing, the depressible member is moved to the depressed position to electromagnetically couple the primary and secondary coils.

Noncontact power transmitting apparatus (TDK Corporation), US 5923544 A

A noncontact power transmitting apparatus which makes it possible to rapidly charge a secondary cell of a part to be charged with large electric power and realize a lightweight and compact part to be charged. A power-transmitting coil of a charging part is divided into two sets, and the power-transmitting coils of the sets are respectively wound around cores, and are formed as a first power-transmitting coil portion 26 and a second power-transmitting coil portion 27 which are separate and independent as the two sets. Meanwhile, a power-receiving coil of a part to be charged is wound around a core, and is formed as a single power-receiving coil portion 28. In a chargeable state in which the part to be charged is placed on the charging part, the power-receiving coil portion 28 is inserted in a space between the first power-transmitting coil portion 26 and the second power-transmitting coil portion 27, and the first power-transmitting coil portion 26, the power-receiving coil portion 28, and the second power-transmitting coil portion 27 are arranged in such a manner as to be aligned with each other. Windings are wound such that the polarities of the windings are adjusted so that the directions of magnetic fluxes φ1 and φ2, which penetrate from the first power-transmitting coil portion 26 and the second power-transmitting coil portion 27 through the power-receiving coil portion 28, are constantly set in the same direction.

Method and apparatus for wireless powering and recharging (Gte Internetworking Incorporated), US 6127799 A

An arrangement is provided for charging a charge storage device by placing the charge storage device in an RF or microwave radiation field. One or more antennas which receive the radiated RF electromagnetic field are placed on the charge storage device. Rectifiers connected to the antennas rectify the received RF electromagnetic field an produce a DC output current which is used to charge the charge storage device. The charge storage device may be a battery or a capacitor and may form an integral part of an electronic device. The same RF field that charges the charge storage device can also be employed to communicate data to transponders which may be associated with computing devices.

Contactless battery charger with wireless control link (Motorola Inc.), US 6184651 B1

In a contactless charging system charging energy is transferred across an inductive coupler to charge a battery (**21**) of a portable device, such as a two-way radio, cellular phone, paging device, or wireless communicator. The inductive coupler also provides a way for communicating at least one signal, such as to improve the charging process and the transfer of charging energy. Charging efficiency is improved by voltage regulation using feedback through the inductive coupler, or via a wireless RF link, and a controller (**11**) in-circuit with the primary side (**12**) of the inductive coupler. The controller (**11**) may communicate information signals via inductive coupling, or via a wireless RF link, for communicating with other devices such as smart cards and microphones or for control or data transfer.

Control of inductive power transfer pickups (Auckland Uniservices Limited), US 6483202 B1

Secondary resonant pickup coils (**102**) used in loosely coupled inductive power transfer systems, with resonating capacitors (**902**) have high Q and could support large circulating currents which may destroy components. A current limit or “safety valve” uses an inductor designed to enter saturation at predetermined resonating currents somewhat above normal working levels. Saturation is immediate and passive. The constant-current characteristic of a loosely coupled, controlled pickup means that if the saturable section is shared by coupling flux and by leakage flux, then on saturation the current source is terminated in the saturated inductor, and little detuning from resonance occurs. Alternatively an external saturable inductor (**1101, 1102**) may be introduced within the resonant circuit (**102** and **902**), to detune the circuit away from the system frequency. Alternatively DC current may be passed through a winding to increase saturation of a saturable part of a core. As a result, a fail-safe pickup offering a voltage-limited constant-current output is provided.

Method and apparatus for supplying contactless power (Meins, Sinsley), US 6515878 B1

A method and apparatus for supplying contactless power. Electrical power is transferred from a power source to a load through a primary energy converter that can be connected to the power source, through a primary inductive loop connected to the primary energy converter and a secondary pickup coil magnetically coupled to the primary inductive loop, and then to a secondary energy converter. The power factor for the transfer of electrical energy is one. Multiple loads can receive power from the power source and, where the loads are located in zones, collisions between the loads can be prevented.

Wireless power transmission system with increased output voltage (IQ-Mobil GmbH), US 6664770 B1

The invention relates to a system for wireless power transmission, which makes it possible to generate an increased voltage on the receiver side using a radio signal that is optimized for this purpose and thereby permits operation particularly of digital semiconductor components in the receiver even if the reciver does not have a power supply of its own.

System, method and apparatus for contact-less battery charging with dynamic control (Koninklijke Philips Electronics N.V.), US 6844702 B2

A system, method and apparatus for contact-less charging of battery operated devices, including a host charger with a power converter and resonant tank circuit and a portable device where the battery is located, with a battery charging control IC, wherein the method obviates the need for a voltage controller in each of both the host and the portable stages. The charging of the battery in the portable device is controlled by a charging controller therein, which is in continual electric communication with the host, whose output power the control IC dynamically monitors and controls. In one embodiment, component count is minimized but battery charging is not optimized when the battery voltage is very low. In the other embodiment, charging efficiency is maximized regardless of the output voltage of the battery.

Inductive coil assembly (Access Business Group International Llc), US 6975198 B2

An inductive coil assembly having multiple coils arranged at distinct orientations to provide efficient inductive coupling of power or communications or both to a device when the device is arranged at different orientations with respect to the inductive primary coil. In one embodiment, the inductive coil assembly includes three coils, each oriented along one of the x, y and z axes of a standard Cartesian three-dimensional coordinate system. The three separate coils provide effective transfer of power and communication when the device is at essentially any orientation with respect to the primary coil. In an alternative embodiment, the multi-axis inductive coil assembly of the present invention can function as a primary to inductively transmit power or communication or both over a plurality of magnetic fields at distinct orientations.

Wireless battery charger via carrier frequency signal (Distefano Michael Vincent), US 7288918 B2

Apparatus and methods to wirelessly charge batteries within a radius of a power source. A power transmitter generates a power signal of specific configuration which is received by the power charger. The power charger harvests the received power signal and stores the energy contained within for the purpose of charging target battery or batteries.

The typical uses of this invention are but not limited to the home, car, office, and work place. Anywhere where rechargeable batteries are used in a device where they need to be placed or physically removed from the device for recharge by conventional wired chargers, this invention provides method to prolong battery life in such a way to extend the time between a physical wired recharge or eliminate such events all together.

Primary units, methods and systems for contact-less power transfer (Splashpower Limited), US 7239110 B2

There is disclosed a system and method for transferring power without requiring direct electrical conductive contacts. There is provided a primary unit having a power supply and a substantially laminar charging surface having at least one conductor that generates an electromagnetic field when a current flows therethrough and having an charging area defined within a perimeter of the surface, the at least one conductor being arranged such that electromagnetic field lines generated by the at least one conductor are substantially parallel to the plane of the surface or at least subtend an angle of 45° or less to the surface within the charging area; and at least one secondary device including at least one conductor that may be wound about a core. Because the electromagnetic field is spread over the charging area and is generally parallel or near-parallel thereto, coupling with flat secondary devices such as mobile telephones and the like is significantly improved in various orientations thereof.

Resonant frequency tracking system and method for use in a radio frequency (RF) power supply (Leslie, Schwenck, Lincoln), US 20030071034 A1

An RF power supply that is capable of tracking rapid changes in the resonant frequency of a load and capable of quickly responding to varying load conditions so as to deliver the desired amount of power. The present invention also provides an RF power supply capable of delivering a wide range of power over a broad frequency range to a load that is remotely located from the power supply. According to one embodiment, the RF power supply includes a direct current (DC) voltage source that provides a DC voltage within a predetermined voltage range; an amplifier, coupled to the DC voltage source, that provides an alternating voltage to a tank circuit connected to an output of the RF power supply; a frequency controller, coupled to the amplifier, to set the frequency of the alternating voltage produced by the amplifier; and a sensor, coupled to the load, to provide a signal to the frequency controller, where the frequency controller sets the frequency of the alternating voltage based on the signal received from the sensor.

System and method for contact free transfer of power (Mobilewise Inc.), US 20070145830 A1

A system and method is provided for the inductive transfer of electric power between a substantially flat primary surface and a multitude of secondary devices in such a way that the power transfer is localized to the vicinities of individual device coils. The contact free power transfer does not require precise physical alignment between the primary surface and the secondary device and can allow the secondary device or devices to be placed anywhere and in arbitrary orientation with respect to the primary surface. Such power transfer is realized without the need of complex high frequency power switching network to turn the individual primary coils on or off and is completely scalable to almost arbitrary size. The local anti-resonance architecture of the primary device will block primary current from flowing when no secondary device or devices are in proximity to the local RF power network. The presence of a tuned secondary device detunes the local anti-resonance on the primary surface; thereby enable the RF power to be transferred from the local primary coils to the secondary device. The uniformity of the inductive coupling between the active primary surface and the secondary devices is improved with a novel multi-pole driving technique which produces an apparent traveling wave pattern across the primary surface.

Bidirectional wireless power transmission (Qualcomm Incorporated), US 20100148723 A1

Exemplary embodiments are directed to wireless power transfer. A wireless power transceiver and device comprise an antenna including a parallel resonator configured to resonate in response to a substantially unmodulated carrier frequency. The wireless power transceiver further comprises a bidirectional power conversion circuit coupled to the parallel resonator. The bidirectional power conversion circuit is reconfigurable to rectify an induced current received at the antenna into DC power and to induce resonance at the antenna in response to DC power.

6.2 Development of Modeling Methodology

6.2.1 Comparison of numerical solvers

Basically, there are two approaches for calculating frequency dependent resistances and inductances, namely

Starting from the charges and current filaments. The partial element equivalent circuit method (PEEC) uses this starting point and employs the concept of partial inductance. The software program "Fast Henry" is based on this technique.

Calculating the electric and magnetic fields by employing appropriate boundary conditions, then deducing S-parameters and equivalent circuit models. Here, FEM techniques are often applied. ANSYS HFSS and MICROWAVE CST are commonly used programs.

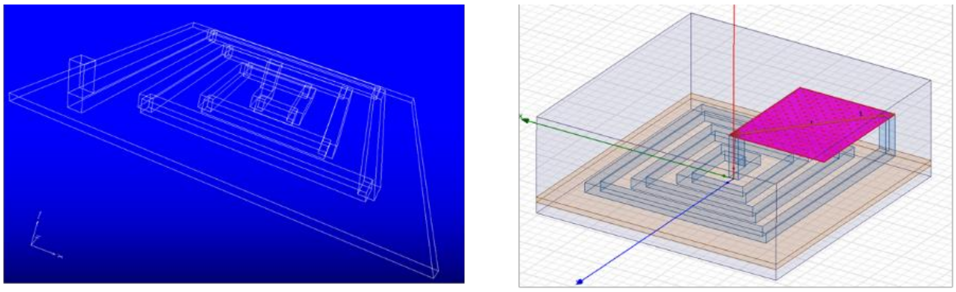
We evaluated a typical coil structure using both Fast Henry and ANSYS HFSS. The deviation between both techniques turned out to be less than 2% (see table 1).

Simulation method	**Real (Impedance) [mOhm]**	**Imag. (Impedance) [mOhm]**
PEEC method, ideal conductors	3.5	73
PEEC method, non-ideal conductors	5.3	75
3D, full-wave, finite element method	5.0	76

Table 1 Comparison of simulation results using PEEC and finite element based simulation methods

Fraunhofer IZM

DraMCo research group



Fast Henry 3D Model | Ansys HFSS 3D Model

Figure 15 Simulation models of planar inductor, left: Fast Henry (PEEC method), right: Ansys HFSS (finite element)

6.2.2 Mohan's Equations for Planar Spiral Inductors

Using ANSYS HFSS, we calculated the values of inductance, resistance and quality factor for various types of planar coils. We then compared the results with the values obtained from Mohan's classical approximate formulas [2]. In their paper, Mohan presents a modification of a formula introduced by Wheeler [3]:

$$L_{quad} = 2.34 * \mu_0 \frac{N^2 * d_{avg}}{1 + 2.75 * \rho}$$

$$d_{avg} = 0.5 * (d_{out} + d_{in}) \qquad \rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$$

N denotes the number of turns, d_{in} and d_{out} denote the inner and outer diameters, respectively. Besides its simplicity, this equation has the advantage of consisting of terms, which can be interpreted easily.

The inductance is proportional to N^2, d_{avg} and roughly inversely proportional to the fill ratio ρ. The latter quantity accounts for the fact that "a full inductor has a smaller inductance because its inner turns are closer to the center of the spiral and so contribute less positive mutual inductance and more negative mutual inductance" [2].

The formula for circular coils is similar and reads:

$$L_{circ} = 2.25 * \mu_0 \frac{n^2 * d_{avg}}{1 + 3.55 * \rho}$$

We also evaluated another expression for L presented in [2], where the concept of geometric mean distance is applied:

$$L_{quad1} = \frac{1.27 \mu_0 N^2 d_{avg}}{2} \left(\ln\left(\frac{2.07}{\rho}\right) + 0.18\rho + 0.13\rho^2 \right)$$

The influence of conductor thickness T is usually neglected, and was therefore studied separately. It turns out that increasing the conductor thickness lowers the inductance, but only to a negligible extent. On the other hand, it lowers the ohmic resistance substantially. (We are practically in the DC realm.)

For the sake of a higher quality factor, thicker conductors are preferrable; a practical value for PCBs is T = 70 µm. We used this value in the following. The conductor spacing S was 200 µm.

6.2.3 Design of Experiment for Choosing Simulation Runs

Mohan's equations depend on N, d_{in} and d_{out}; we used N, d_{in} and the conductor width W instead, from which d_{out} can be calculated. For choosing proper data sets for the simulation runs, we employed ideas from DoE (Design of Experiment): The independent variables or factors are not studied one-at-a-time, but rather simultaneously by considering them as components of an n-dimensional hyperspace (in our case n=3).
If we require $10 \le N \le 20$, $200\mu m \le W \le 600\mu m$, and $2mm \le d_{in} \le 6mm$, the design space becomes a cube (Figure 16). Taking the vertices, the midpoints of the edges and the center points of the faces and the cube, one gets a three-level full factorial design. We chose the simulation runs accordingly.

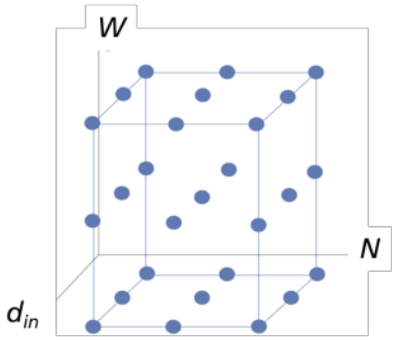


Figure 16 Design space for the simulation runs

6.2.4 Discussion of Numerical Results

It comes as no surprise that Mohan's equations provide excellent approximations (deviation less than 4.5%). Especially when considering wider coils, the overall agreement obtained with the Wheeler-type equation was slightly better, so we used this expression.

We present the results from our simulations in the following table, because they give an impression of what values for L and Q can be typically achieved.

Windings (10, 15, 20)	Conductorwidth [um] (200, 400, 600)	d_{in} [mm]	L@100kHz [uH]	Q@100kHz	"footprint" d_{out} [mm]
10	200	2	0,6213	1,3204	9,6
10	200	4	0,95194	1,5273	11,6
10	200	6	1,3462	1,7091	13,6
10	400	2	0,74882	2,3376	13,6
10	400	4	1,0705	2,6573	15,6
10	400	6	1,4253	2,9102	17,6
10	600	2	0,90688	3,2182	17,6
10	600	4	1,2418	3,5934	19,6
10	600	6	1,5753	3,8818	21,6
15	200	2	1,7355	1,8114	13,6
15	200	4	2,4681	2,0403	15,6
15	200	6	3,2732	2,2328	17,6
15	400	2	2,2585	3,2645	19,6
15	400	4	2,9263	3,5508	21,6
15	400	6	3,6598	3,8024	23,6
15	600	2	2,7729	4,4553	25,6
15	600	4	3,4018	4,7402	27,6
15	600	6	4,0735	5,0037	29,6
20	200	2	3,6929	2,2724	17,6
20	200	4	4,918	2,4917	19,6
20	200	6	6,2477	2,6826	21,6
20	400	2	4,9094	4,0505	25,6
20	400	4	6,0267	4,3034	27,6
20	400	6	7,2076	4,5298	29,6
20	600	2	6,0549	5,4406	33,6
20	600	4	7,1007	5,6795	35,6
20	600	6	8,1902	5,8963	37,6

Figure 17 Values for L and Q for PCB coils with typical dimensions - w/o ferrite

These values are valid for coils without ferrite. The effects of a ferrite layer being placed beneath the coil are discussed further below.

Interestingly, the same value for d_{out}, which one might regard as the footprint of the structure, may be attained for different data sets, (e.g., for d_{out}=17.6 mm there are 4 possibilities). As expected, the inductance is highest for the highest number of windings. For a fixed number of windings, it is advantageous to make d_{in} as large as possible. On the other hand, if the quality factor is decisive, it is the conductor width which should be chosen as large as possible.

6.3 Comparison of Coil Performance in Different Technologies

In addition to printed circuit board as substrate technology for the realization of the use of ceramics based LTCC technology was evaluated. Both technologies allow the fabrication of multilayer substrates with comparable conductor trace and spacing dimensions. However, as LTCC substrates are sintered at very high temperatures (approx. 800°C) the conductors have to be screen printed from pastes filled with metal particles. The specific electrical conductivity of the pastes is lower than that of the metal foils. The lower electrical conductivity affects the conductor losses and reduces the quality factor of the inductors.

In order to assess the influence of the substrate technology on the electrical performance of the inductors the test samples defined in the DOE were simulated using electromagnetic field simulations. The results show that the resistance of the identical geometry (number of windings, number of layers, conductor widths and spacing) is increased by a factor of approx. seven compared to PCB coils. As a results of the increased resistance the quality factor of the LTCC coils is reduced. At a frequency 100 kHz the quality factor of LTCC coils is only 10 % of PCB coils, limiting the transfer efficiency.

6.4 Impact of Process Tolerances

In order to assess the usability of substrate integrated coils the variation of the electrical performance due to process variations will be investigated. The process variations may occur due to geometrical or material variations in the conductor, insulator or magnetic core materials. As described above, the analysis was done using electromagnetic (EM) field simulations of the coils.

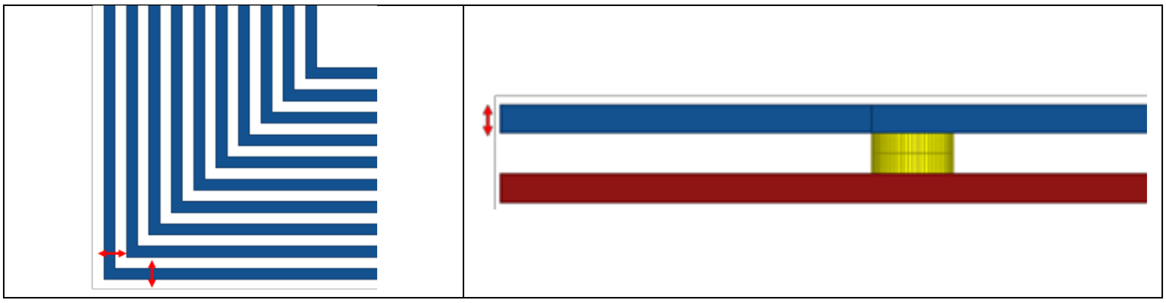


Figure 18 Detail of geometry of test coil for tolerance analysis, left: top view, side view

In this case, the 3D full-wave solver AnsysEM Maxwell (Eddy Current Solver) was used.

In order to assess the impact of process tolerances the geometry of the coils was changed in the simulation. Table 2 shows the impact of the variation of the trace width. An increase in the trace width is expected to reduce both the inductance and the resistance due to the lower current density in the traces.

	L [uH]	R [mOhm]
Width -10%	1.61	691
Nominal Width	1.60	553
Width +10%	1.59	462

Table 2 Effect of line width on electrical performance

The EM simulations show the expected behaviour with a change in inductance and resistance of approx. 1% and 20% respectively.

A change in the metal thickness was expected to change electrical parameters of the coil in a similar fashion to the trace width.

	L [uH]	R [mOhm]
Thickness -10%	1.61	616
Nominal Thickness	1.60	553
Thickness +10%	1.60	503

Table 3 Effect of metal thickness

Looking at the results in Table 3 it can be seen that the effects in terms of inductance and resistance are approx. 1% or below and 10% respectively. In comparison with the trace width the effect of the thickness is less pronounced.

6.5 Stacked Coils

We employed field simulations to investigate multilayer coils based on the quadratic designs we discussed at the beginning. The inductors are connected in series.

Theory predicts (see [4], p. 81) that for tight coupling between the layers, *L* obeys the power law:

$L=L(1\_layer)*n\_layers^2$.

For two layers this expression becomes $L=L(1\_layer)*4$ and may be interpreted as follows [4]:

$$L = L_1 + L_2 + 2M$$

L_1 and L_2 denote the self-inductances of the individual spirals and M is the mutual inductance between them.

$$M = k\sqrt{L_1 L_2}$$

k is the coupling between the inductors. For two identical spirals and $k \cong 1$ we get the factor of 4.

In practice, we also observe a power law, albeit with an exponent somewhat lower than 2.

6.5.1 "Small" Coils

As a first example, we consider stacks of identical coils with N=10, w=200µm, d_{in}=2mm and a vertical (inter-layer) distance of dz=150µm.

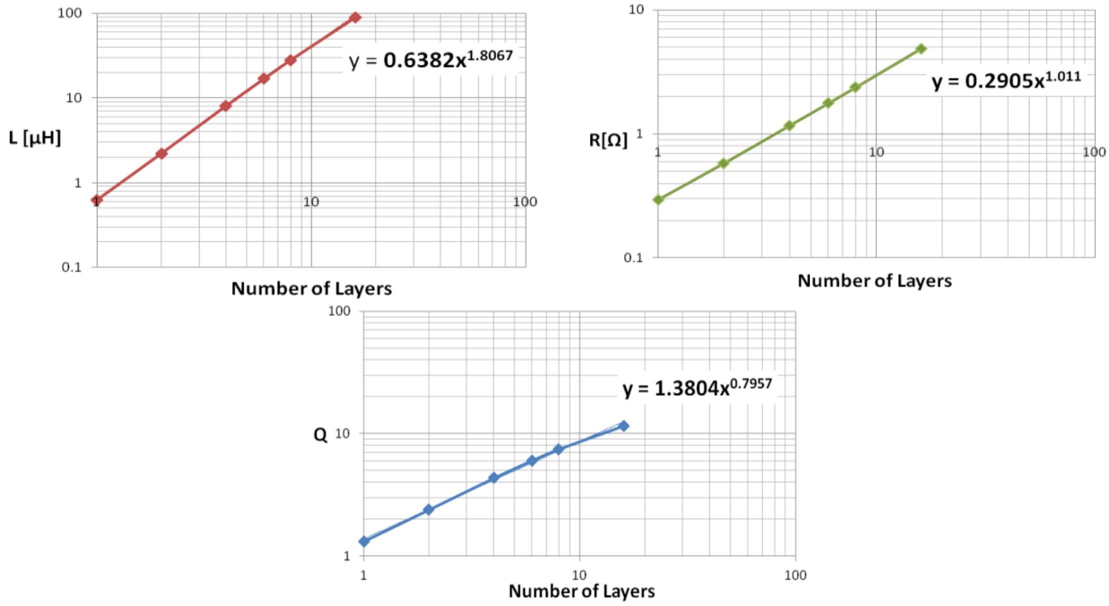


Figure 19 Values for L, R, Q as a function of the number of layers for a "small" coil

The power law for *R* comes as no surprise. We obtain for *Q* a power law, too, with the exponent lowered by the exponent for *R*.

6.5.2 "Large" Coils

As an example of a "large" coil, we take spirals with N=25, w=600µm, d_{in}=6mm as building blocks, the interlayer distance stays the same (Figure 20).

The exponent for *L* increases – approaching 2 - since the enlargement of the coils results in a tighter coupling between the layers.

The exponent for *R* is now 1.3 as opposed to almost 1 in the first example, making this relation less trivial. Moreover, *R* (and thus *Q*) exhibit deviations from the power law. This is a consequence of the proximity effect.

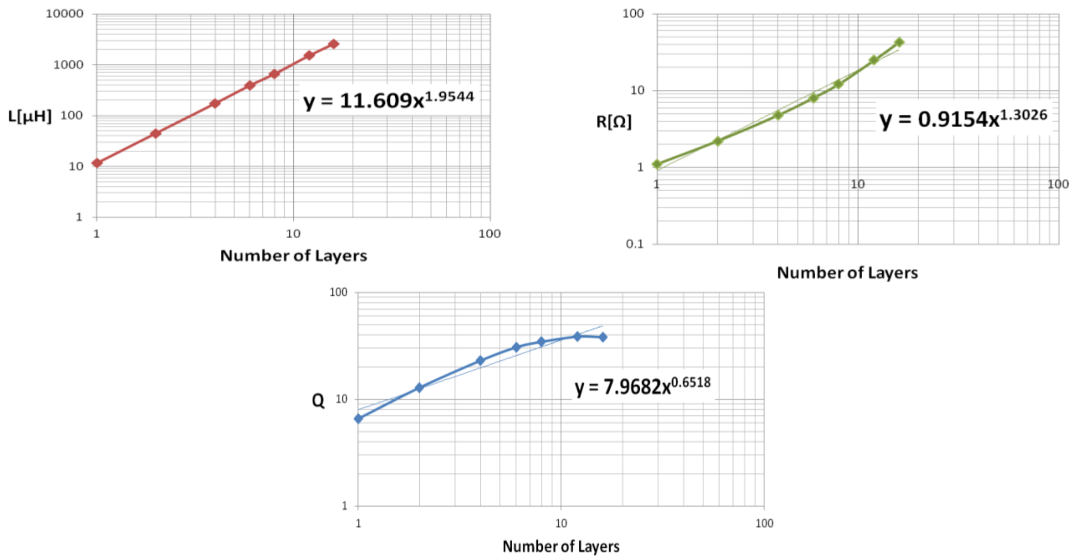


Figure 20 Values for L, R, Q as a function of the number of layers for a "large" coil

6.5.3 Influence of Interlayer Distance

We then considered a spiral inductor with N=15, w=400µm, d_{in}=4mm and varied the interlayer distance dz. In Figure 21, only the extreme values dz=100µm and dz=600µm are shown.

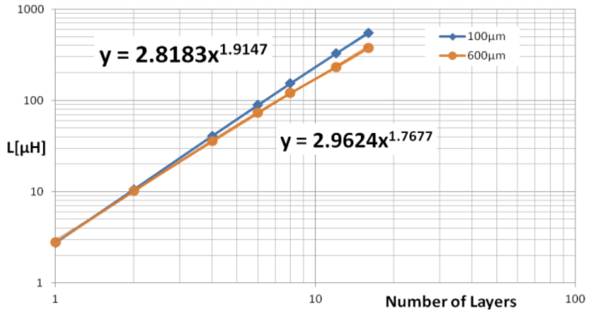


Figure 21 Exponent for L depending on the interlayer distance dz

The exponent grows with decreasing dz (resulting in tighter coupling).

6.5.4 Staggered Coils

In case of planar inductors with evenly spaced turns, the magnetic field has a pronounced maximum above the center of the coil. To increase the homogeneity of the magnetic field, „staggered" coils are employed. Figure 22 shows an example. The conductor width increases when moving towards the center, while the turn density decreases. More details will be provided in the next section.

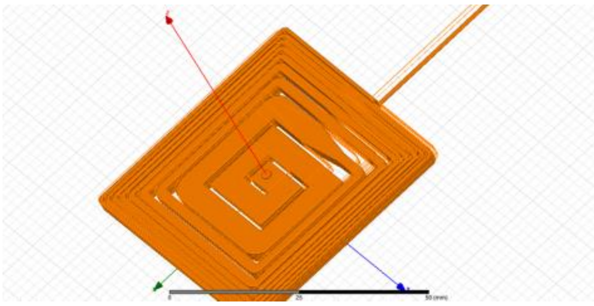


Figure 22 Simulation model of a staggered coil

If one stacks coils with conductors as wide as in Figure 22, one expects a large proximity effect.

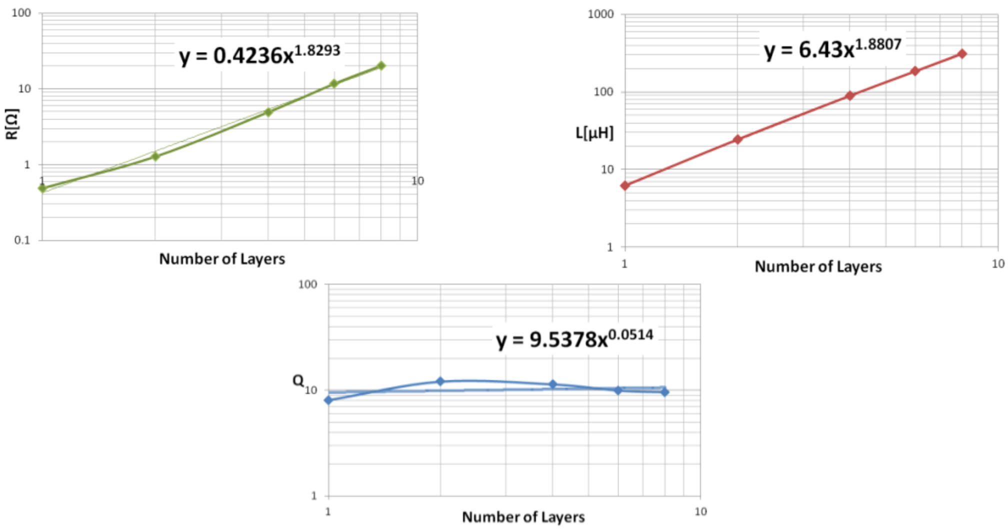


Figure 23 Values for L, R, Q, as a function of the number of layers for a "staggered" coil

Indeed, while L behaves similar to the „normal“ coils, the proximity effect is so strong that the trend line for R rises almost with the same exponent as L. The actual curve for R is even slightly convex, so that Q eventually decreases. For this type of staggered coils, it is only reasonable to stack at most two coils.

6.5.5 Comparison Through-Hole Via - Blind Vias

Considering cost efficiency, one tries to avoid buried vias. Therefore, we studied the multilevel inductors both with buried and through-hole vias. Since the difference turned out to be very small, we advocate the use of through-hole vias.

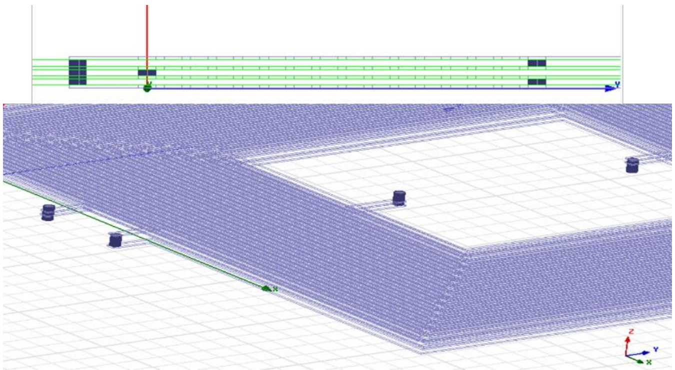


Figure 24 Thru hole vs blind vias - simulation set-up

4 layers	D_in	6			8			10		
	Sep (um)	L (uH)	R (Ohm)	Q	L (uH)	R (Ohm)	Q	L (uH)	R (Ohm)	Q
Coil14_through	150	49.5065	2.2919	13.5723	59.2979	2.5875	14.399	69.2363	2.8828	15.0905
Coil14_blind	150	49.8872	2.3006	13.6246	59.7294	2.6036	14.4141	69.7829	2.8991	15.1239

Table 4 Thru hole vs blind vias - electrical parameters

6.6 Staggered Coils - Homogeneity of the magnetic field

As mentioned above, in case of planar inductors with evenly spaced turns, the magnetic field has a pronounced maximum above the center of the coil. To increase the homogeneity of the magnetic field, IZM, following a suggestion from KU Leuven, has thoroughly investigated spiral coils, where the widths of the conductors of the spiral and the spacing between them need not be equal. At first, no ferrites were considered.

The initial coil design was:

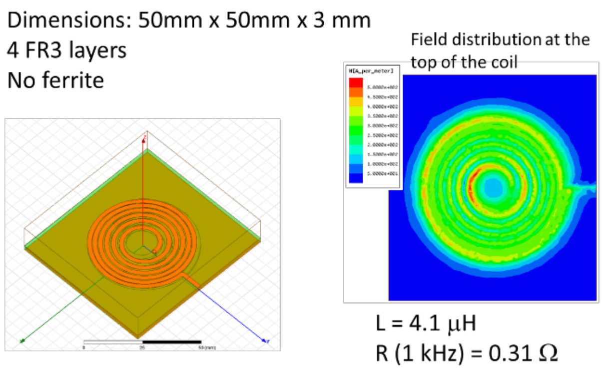


Figure 25 Initial coil design (left) and simulated magnetic field distribution (right)

An even spiral may be parameterized using

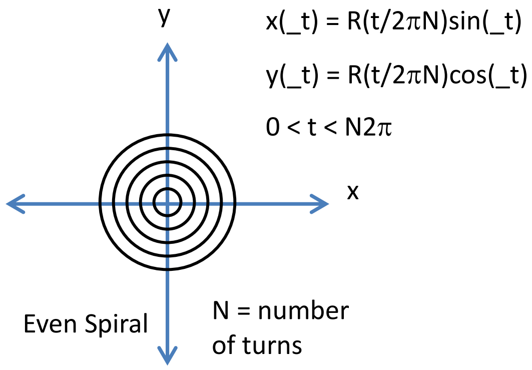


Figure 26 Parameterization of planar coil with even spacing between windings

Introducing an exponent P yields an “uneven” spiral.

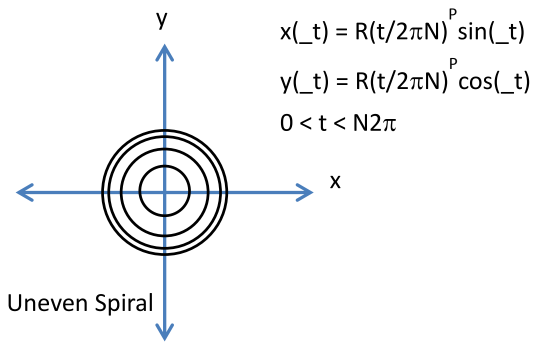


Figure 27 Parameterization of planar coil with uneven spacing between windings

For P = 1: spiral with even distances

For P < 1: falling distances moving away from the center

For P > 1: rising distances moving away from the center

For typical values the layouts of the inductors look like this:

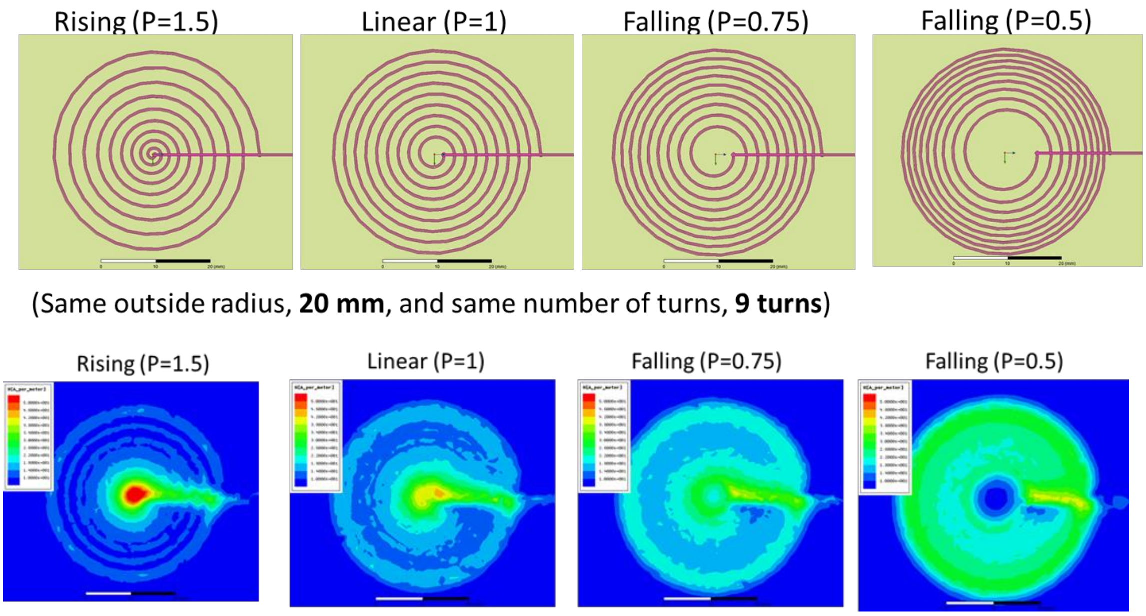


Figure 28 Effect of uneven winding separation on magnetic field distribution

The effect on the homogeneity of the magnetic field is rather striking.

In this case, it was evaluated 2mm above the coil, but the effect is similar at greater distances. (The strength of the magnetic field decreases, of course.) Checking the frequency dependence, one finds that the results are practically identical for 1 kHz and 10 kHz.

Even the eye in the middle can be eliminated by extending the spiral to its center:

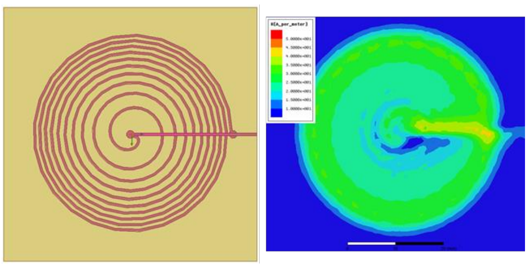


Figure 29 Optimized winding layout for homogeneous field distribution of transimitter coils

Rather than decreasing the gaps, one might try to decrease the conductor line (TML) widths. As expected, the resistance decreases, but so does the inductance. Thus, the overall impact on the quality factor is not that significant.

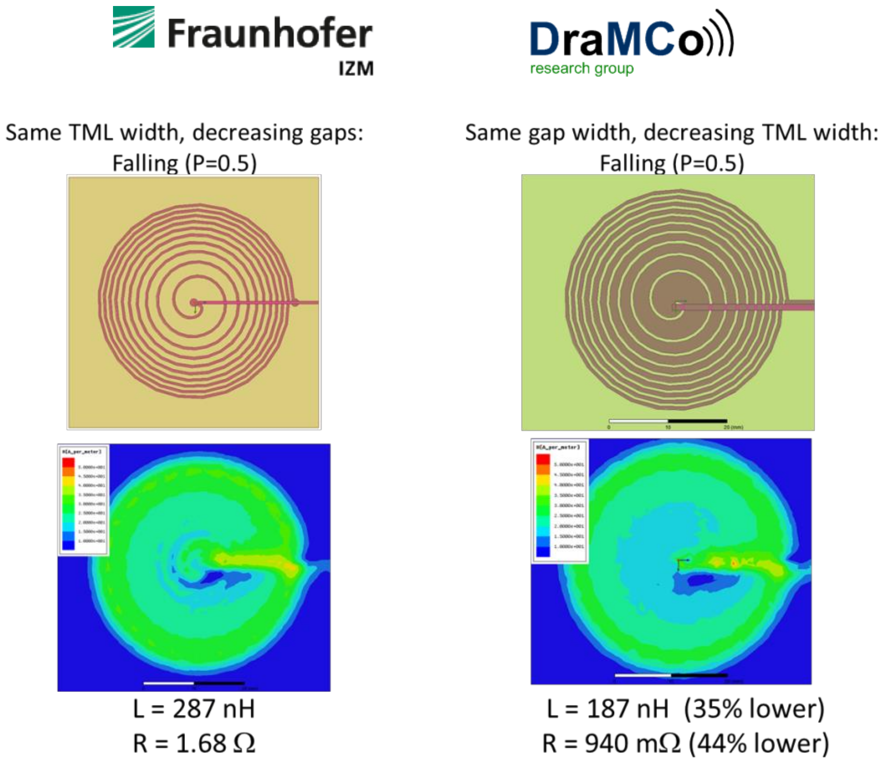


Figure 30 Comparison of uneven coils with interchanged metal traces and gaps

In case of two stacked coils, the homogeneity of the field is similar:

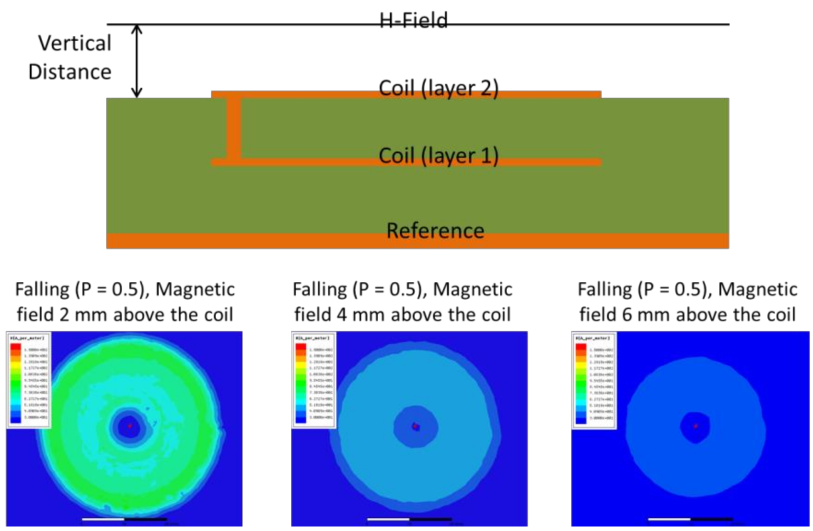
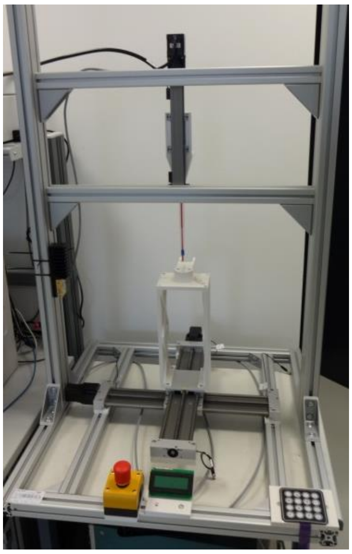


Figure 31 Field distribution of stacked uneven spaced coil windings

6.6.1 Development of Field measurement system

Figure 32 shows the automatic measurement set-up that was designed during the project. The measurement is based on a near-field probe for the determination of the magnetic field at a given position of the device under test. The DUT coil can be moved in the horizontal and vertical position so that the field distribution over a prescribed area can be measured. The coil is excited by a signal with given amplitude and frequency so that frequency dependent measurements can be done. The field probe contains a small loop as the sensor element for the magnetic field. As the charging current in the receiver coil is induced by the magnetic fields created by the transmitter coil, the magnetic coupling factor can be derived from the measurements of the field distribution.



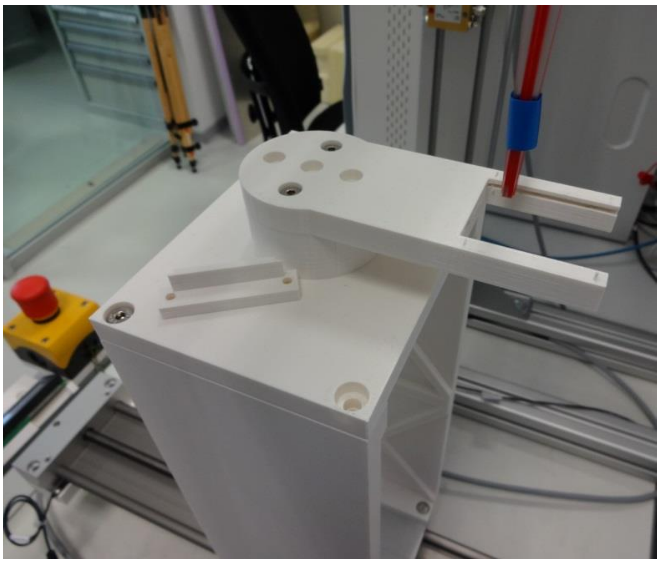


Figure 32 Set-up for measuring the magnetic field and the coupling factor
left: field probe on automatic manipulator; right: field probe over coil fixture

In addition to the determination of the coupling factor the set-up can also be used for measurements of the impact of misalignment between coils. While the receiver coil is fixed in the top fixture the transmitter coil can be moved in the lower fixture determining the impact of horizontal and vertical misalignment between the coils.

During the project the positioner was enhanced by motorizing the DUT fixture and construction of an automatisation of the measurement set-up. The automated measurement system features a resolution of approx. 100 µm.

7 Coils in Substrate: Realization

The design of coils for wireless transformers requires electrical models for the inductance and quality factor. The models have been derived from electromagnetic (EM) field simulations based on a design-of-experiments approach for the selection of model test cases. In order to test the validity of the model test samples have been fabricated and measured.

7.1 Design of Test Samples

The electrical model describes the characteristics of planar coils based on a printed circuit board (PCB) technique. The coils are to be used in the test case of the wireless mouse. The coils were designed based on standard PCB design rules with a minimum trace width and spacing of 100um, a minimum metal thickness of 17um and a maximum of eight metal layers. Standard FR4 was used as the substrate material.

Designs included variations of the transmitter and the receiver coil (see Table 5 and Table 6).

DUT number	1	2	3	4	5
Test structure	Case1 RX 2layers	Case1 RX	Case1 RX 2layers	Case1 TX	Case1 TX

Table 5 Designation of test structures

DUT number	6	7	8	9	10
Test structure	Case1 RX	Case2 RX	Case2 TX	Case2 TX	Case2 RX

Table 6 Designation of test structures, continued

The coils were based on single and double layer coils with a metal thickness of 70um. The coils were made from copper and covered with a nickel based surface finish to prevent corrosion. The test samples can be seen in Figure 33.

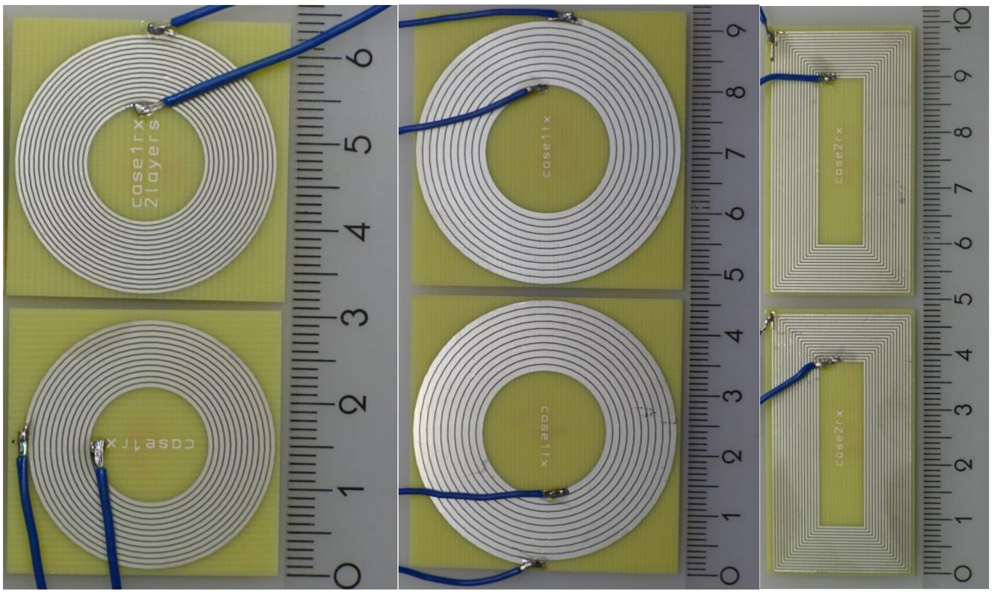


Figure 33 Test samples for transformer coils

7.2 Measurement of Test Samples

In order to characterize the electrical performance S-parameters were measured in the frequency range from 1 kHz to 20 MHz. While power transmission is usually done at around 100 kHz it was checked if the coils could be used for RFID applications in the HF-band (13.56 MHz). The measurements were done using an Impedance analyzer (Agilent 4294A) with a test fixture. The instrument was calibrated using an open-short calibration.

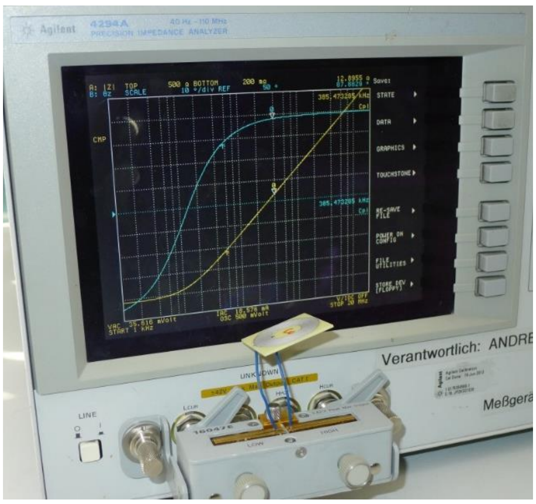


Figure 34 Measurement set-up for characterizing the electrical characteristics of the coils

The test samples were attached with a length of 5 cm of Litz wire to connect the wires to the test fixture. The inductance and the quality factor was derived from the complex impedance by assuming an L-R series equivalent circuit for the measurement results.

The effective inductance derived from the measurements can be seen in Figure 35. The transmitter coils ('TX') tend to have higher inductance values than the receiver coils ('RX') because of larger diameter. All test samples show a flat inductance in the frequency range up to approx. 100 kHz. The inductance decreases slightly due to the skin effect and the reduction of the internal inductance due to flux in the windings.

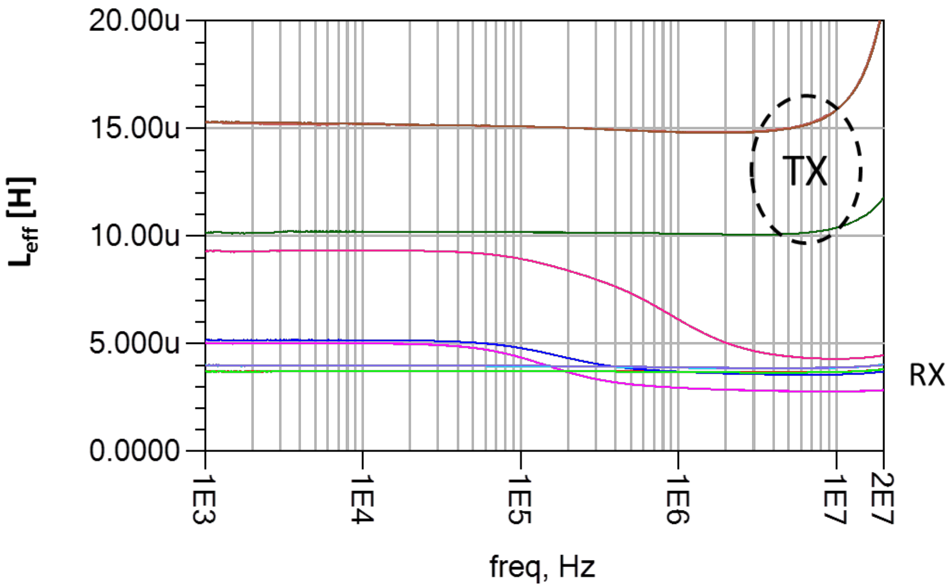


Figure 35 Effective inductance of test samples

Towards higher frequencies the large TX coils show an increase in the effective inductance. This effect is due to the parasitic capacitance between the windings which introduce an L-C resonance.

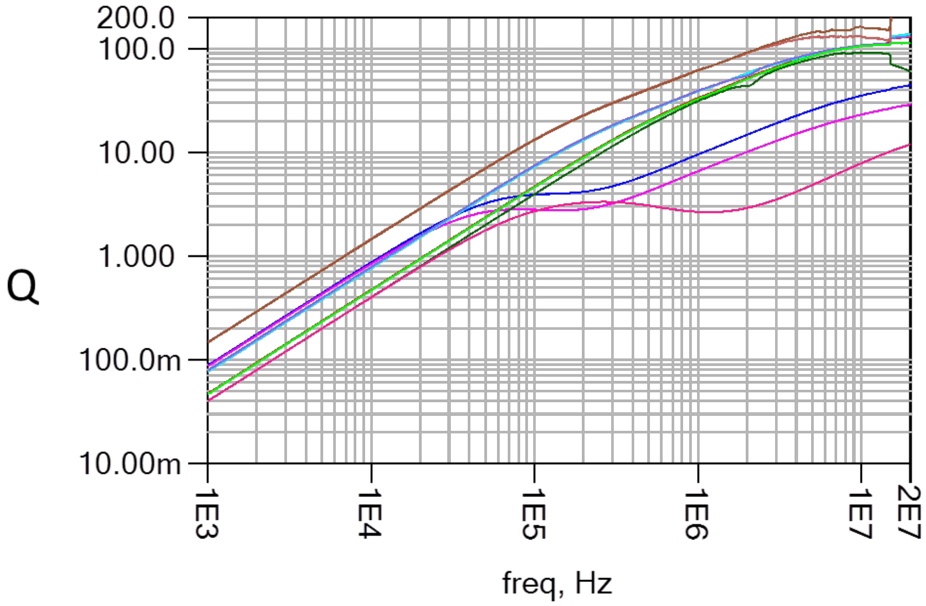


Figure 36 Quality factor of test samples

The quality factors of the coils can be seen in Figure 36. The coils show maximum quality factors between 10 and 130 at approx. 10 MHz and 10 at 100 kHz.

7.3 Comparison Measurement and Model

In order to validate the model of the coils a comparison for selected coils has been done. The results show good correlation between the model and the results from the EM field simulations with an error of < 2%.

	Measure-ment [µH]	Formula	Error %	Measure-ment 2 [µH]	Simulation
Coil1Rx	3.7	3.636	1.7	3.697	3.646
Coil1Tx	3.96	3.88	1.9	3.96	4.01
Coil2Tx	15.21	15.48	1.75	15.23	15.47

Table 7 Comparison of test sample measurements and analytical/numerical calculations

8 Ferrite in Substrate: Modeling

8.1 Literature Review

The design of magnetic core coils has been an issue for quite some time. There are several materials with different magnetic properties. Van den Bossche gives an overview and classification with respect to possible applications (cf. Figure 37)

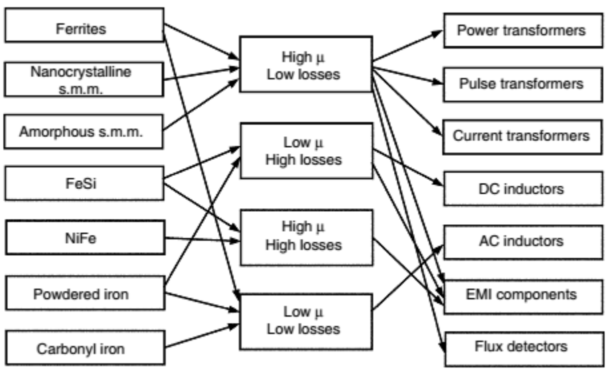


Figure 37 Overview of magnetic materials, their properties and applications [van den Bossche]

For power transmission it is advantageous to reduce losses in the magnetic core and have a high magnetic coupling between the primary and secondary coils thus materials with high permeability and low magnetic losses are used. Some examples of numeric values are given in Table 8 and Table 9.

Material	FeSi, laminated	NiFe, Ni-steel, laminated			Powdered Iron	Carbonyl Iron
Contents	3-6% Si	Permalloy 80% Ni	Isoperm 50% Ni	Invar 30-40% Ni	95% Fe	92.5% Fe
Permeability	10^3-10^4	10^4	3 10^3	2 10^3	1-500	1-50
ρ, uΩm	0.4-0.7	0.15	0.35	0.75		> 10^6

Table 8 Properties of selected magnetic materials

Material	Ferrites	Amorphous		Nanocrystalline
Contents	MnZn, NiZn	73.5% Fe	70-73% Co	73.5-90% Fe
Permeability	10^2-2 10^4	10^4-1.5 10^5	10^4-1.5 10^5	1.5 10^4-2 10^4
ρ, uΩm	10^2-10^4 MnZn 10^2-10^4 NiZn	1.2 – 2	1.4 – 1.6	0.4-1.2

Table 9 Properties of selected magnetic materials (continued)

In addition the materials tend to have a pronounced frequency dependency. Figure 38 shows an example for a nano crystalline material. While the low-frequency permeability is very high the values decrease at higher frequencies. The frequency at which the decrease sets in and the initial permeability depend on the material.

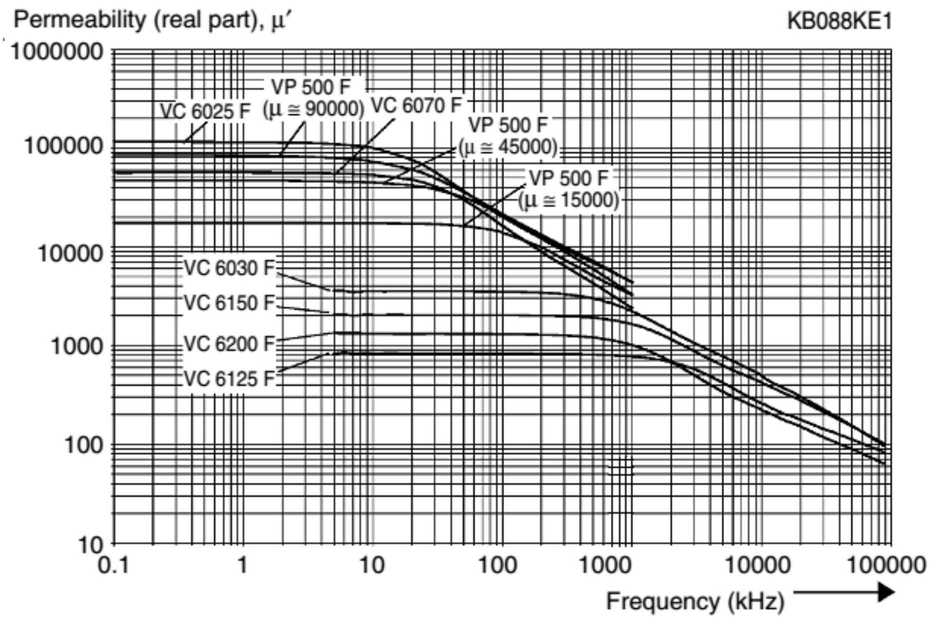


Figure 38 Frequency Dependency of Vitroperm material

The materials can be integrated into the manufacturing of planar substrates using different technologies. A method similar to the design of non-planar coils uses ferrite cores that are manufactured in a specific shape. These can be bought from electronics distributors in various shapes. Figure 39 shows an example of a ferrite sheet that has been integrated into the design of a planar inductor. The comparison of the inductance shows a nearly linear increase with the thickness of the magnetic film.

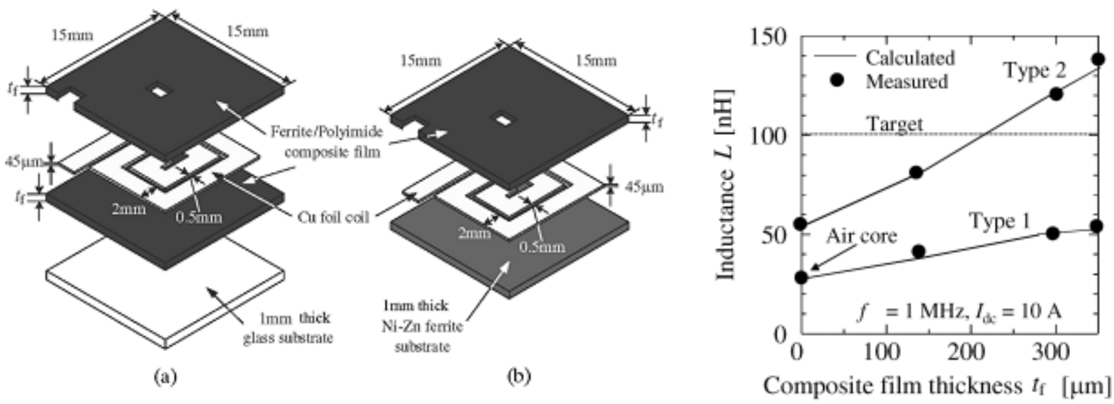


Figure 39 Integration of magnetic sheets into planar substrate

Another option to include the magnetic materials is to mix magnetic particles into an epoxy resin that is compatible with the lamination process of PCBs. Figure 40 shows a cross section of substrate. When the substrates are thin they also can be made flexible.

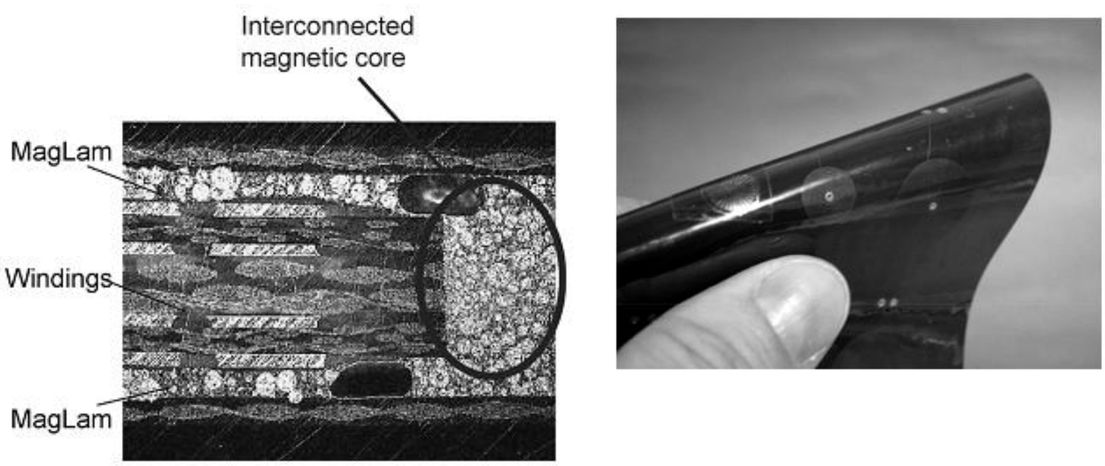


Figure 40 Cross section of PCB made with magnetic particles in epoxy matrix

Some metals that are compatible with PCB manufacturing, e.g. nickel, have magnetic material properties. They can be integrated into the design by electrodeposition or sputtering. This allows for layers with low height in the range of some microns. Figure 41 shows an example of an inductor for a DC-DC converter.

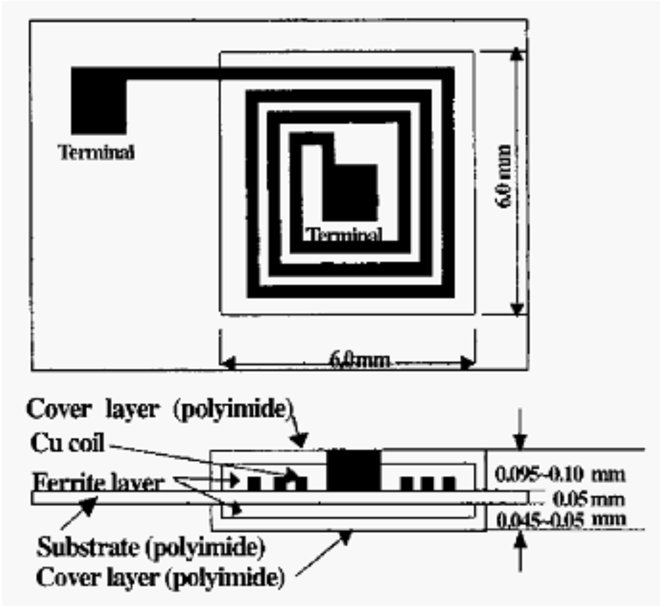


Figure 41 Substrate integrated coils with electrodeposited ferrite layer

Other publications have looked into the design of the magnetic layers for the coils. Figure 42 shows the use of ferrite stripes assembled in a star shape to reduce the dependency of the magnetic coupling factor on the alignment of primary and secondary transformer coil.

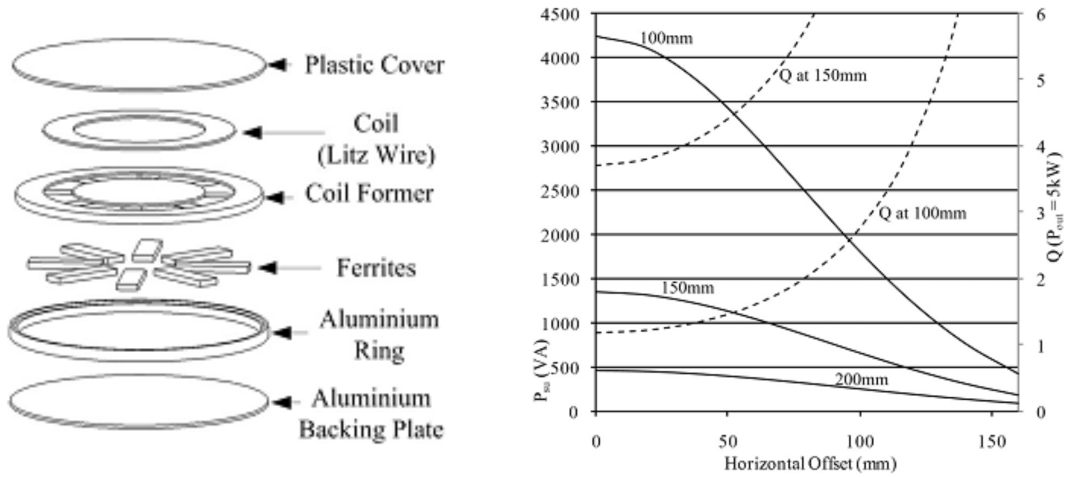


Figure 42 Star shaped ferrite elements in planar inductor design

In order to integrate the ferrites into the substrates different technologies have been used. Examples of magnetic ore coils can be seen in figure 43and figure 44.

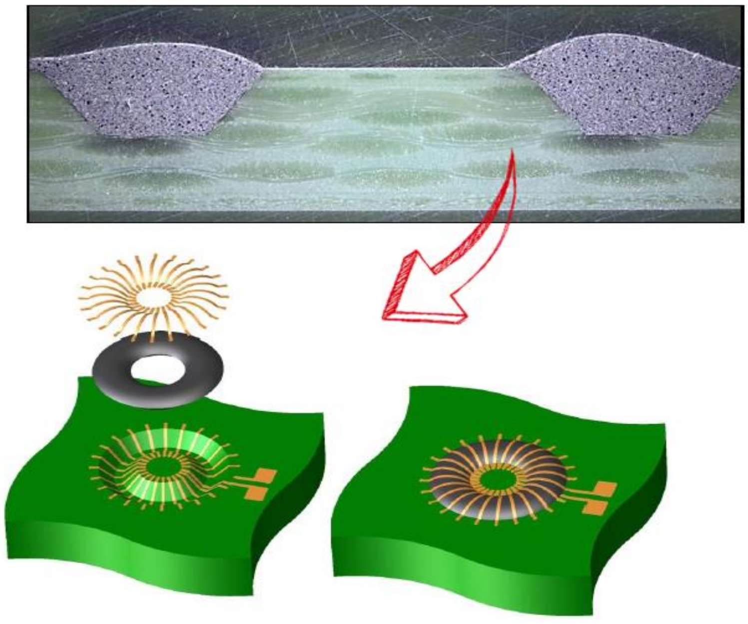


Figure 43 Ferrite core integration into PCBs for toroidal inductor

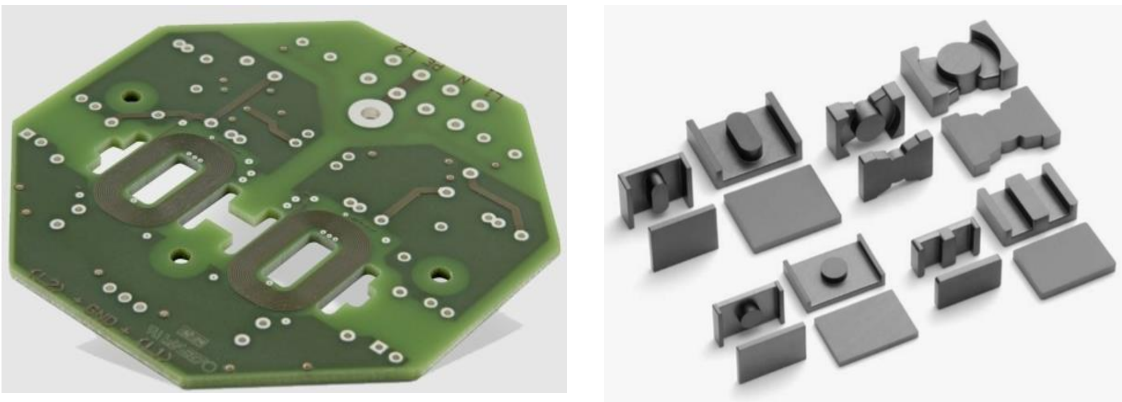


Figure 44 Ferrite preforms (right) for magnetic core inductors for assembly into PCB coils (left) from TDK

8.2 Impact of Ferrites on Coil Performance

Using electromagnetic (EM) field simulations the impact of magnetic materials on the inductance was investigated. The simulations were done using a 2D full-wave field solver (AnsysEM Maxwell, Eddy Current solver). Three configurations were compared (see Figure 45). The ferrite used had a permeabilty of 1000. For the comparison the per-unit-length inductance of the conductor traces were compared.

Figure 45 Cross section of simulation models for assessment of ferrite placement

Figure 46 shows the self-inductance of the coil traces. For all ferrite configurations the self-inductance increases with inceasing diameter as the magnetic flux is higher. All traces show the reduction of the inductance due to the the skin effect. With regard to the placement of the ferrite core it can be seen that only the placement below the conductor traces increases the inductance of the coils by approx. 50%.

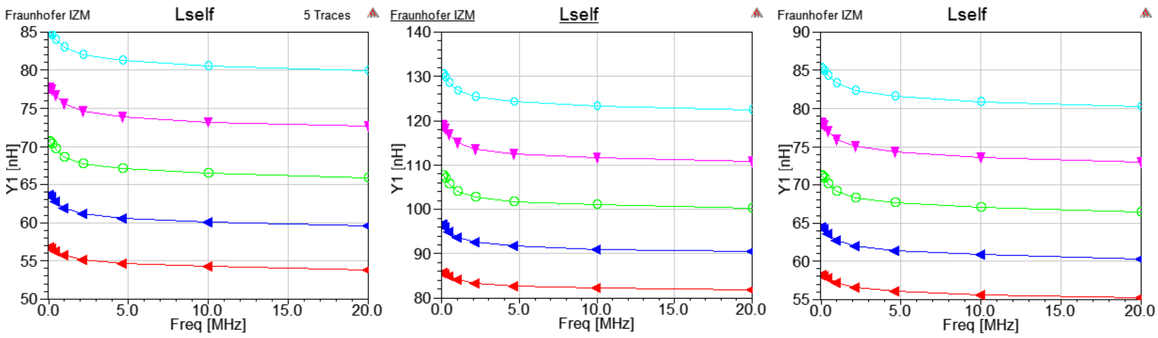


Figure 46 Influence of ferrite placement on self-inductance

The mutual inductance between the individual traces of the coils is also only affected by the placing the ferrite below the traces by aprox. 100%.

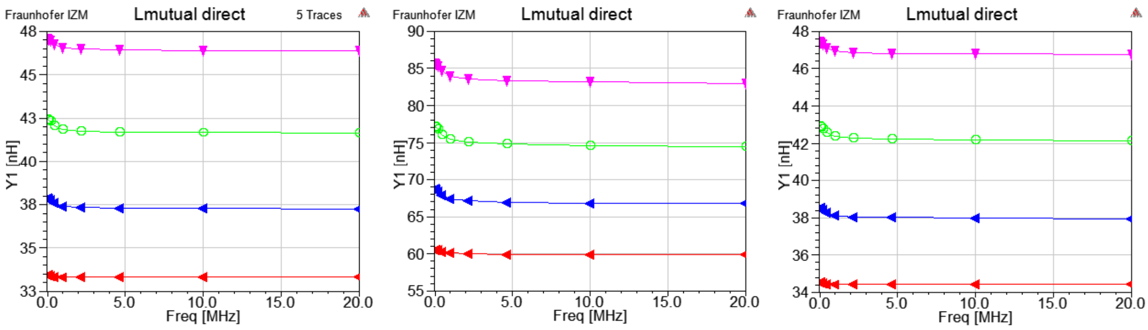


Figure 47 influence of ferrite placement on mutual inductance of coil traces

If the core height in design number three is varied it can be seen that an increse in the core height affects the traces in direct vicinity to the core stronger than traces that are farther away. The increase of both the self- and mutual inductance for the trace directly adjacent to the core is about 20% while the incresae for the outermost trace is only 5%.

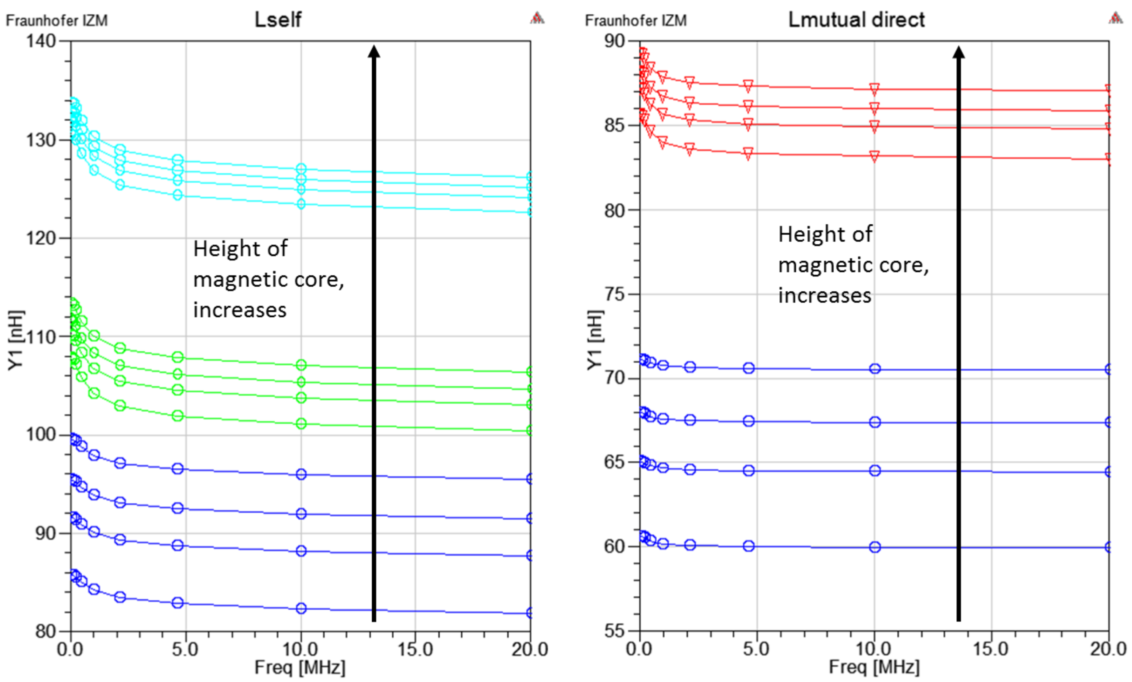


Figure 48 Influence of magnetic core height on trace inductance

8.3 Modelling Methodology

Generally speaking, ferrite layers serve three purposes:

- Shielding
- Increasing the strength of the magnetic field
- Shaping the magnetic field

The shaping is caused by the boundary conditions that force the magnetic field lines to be perpendicular to the ferrite. It concentrates the field and may thus help to increase the coupling between the transmitter and receiver coils. We verified all three aspects by numerical field simulations.

The magnets we used for the PCB samples were commercially available ferrite layers placed 1mm beneath the coils (with FR4 in between). To facilitate integration into the PCB, we only used the plate part of an E-transformer core. It was made out of 3F4 ferrite from Ferroxcube®, similar to the material mentioned in the Qi standard. The layer beneath Case1Rx was 0.75mm thick, the one beneath Case1Tx 2.5 mm.

The influence of both ferrite thickness and relative permeability were also studied. When relative permeability increased or decreased by 20% of the nominal value (900), inductivity varied up to 0.24% of the obtained value for the nominal case. When doubling or dividing by two the thickness of the ferrite, on the other hand, inductivity fluctuates up to 3.12% as compared to the value for the nominal thickness.

Figure 17 lists values for coils without ferrite. If a ferrite layer is placed beneath the coil, estimates for *L* and *Q* can be obtained by multiplying these values by a factor which is plotted in Figure 49 as a function of the distance between coil and ferrite (assuming a permeability of 1000).

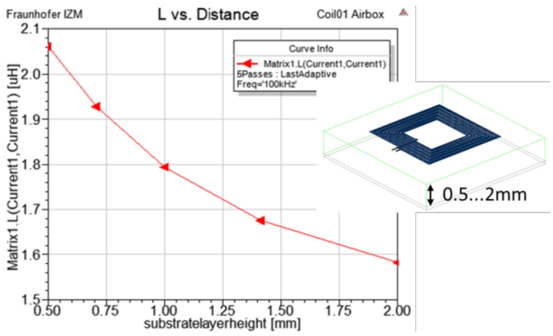


Figure 49 "Ferrite factor" for L and Q as a function of the distance between inductor and ferrite layer (μ_r = 1000)

9 Ferrite in Substrates: Realization

9.1 Design of Ferrite Coils

As was shown in previously the material properties of the ferrite layer have a strong impact on the inductance of the transformer coils. Material suppliers specify only a typical value at a given frequency. As the permeability is frequency dependent measurements were performed of ferrites. The measurement uses a toroid shaped material sample that is inserted into a coaxial metallic test fixture with a known electrical impedance. The current flow through the center conductor and returning through the outer conductor induces a cylindrical magnetic field in the material sample. From the change in impedance of the test fixture with the material sample the permeability can be determined. Figure 50 shows the measurement set-up including the test fixture and the impedance analyser.

An example of the frequency dependency of a ferrite material is shown in figure 51. The permeability decreases with increasing frequency. At 1 GHz the permeability is almost one rendering the material non-magnetic.

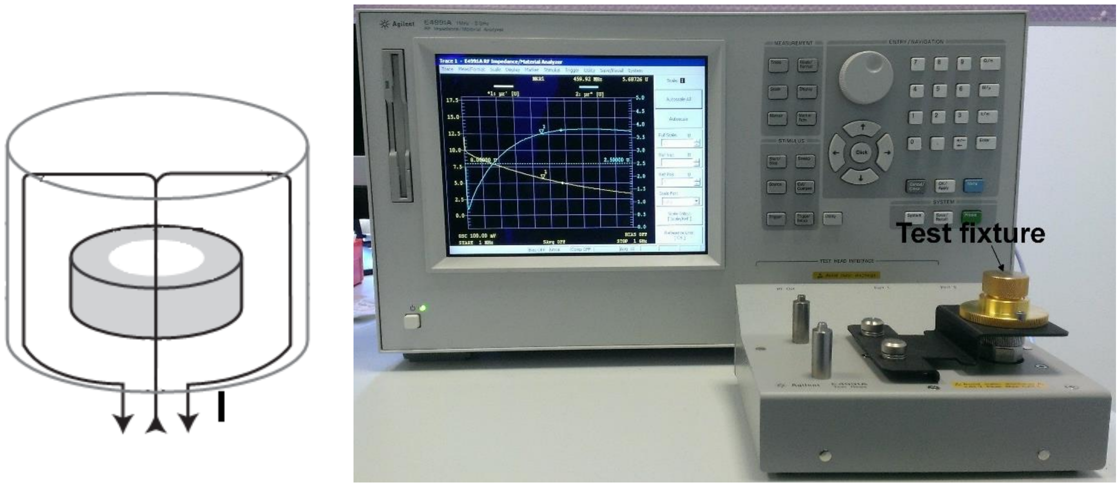


Figure 50 Left: Measurement principle for magnetic material properties with toroidal material sample (grey) in coaxial test fixture; Right: Measurement set-up for determination of permeability with test fixture (left) and impedance analyser

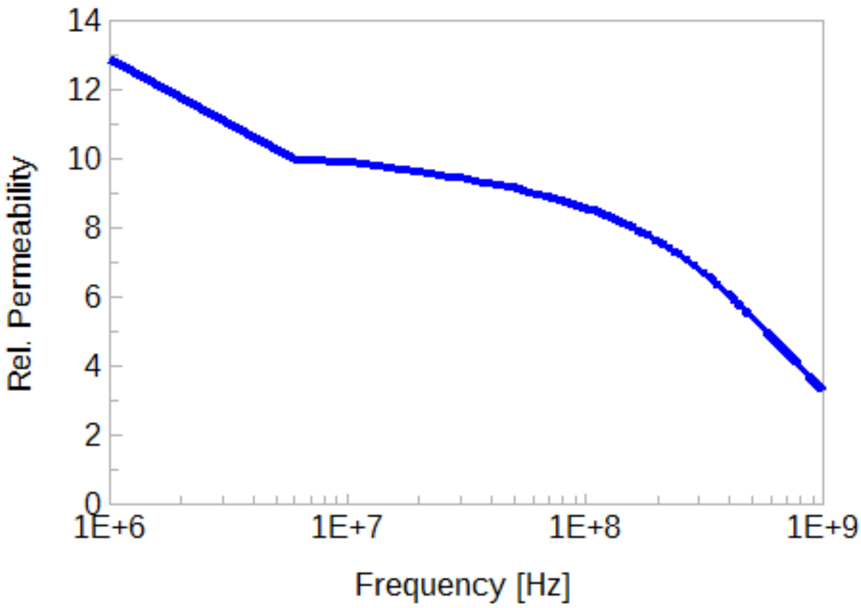


Figure 51 Frequency dependency of permeability

9.2 Fabrication of Test Samples

The test samples were fabricated based on a standard multi-layer PCB manufacturing process. The Coils were formed from traces in the metal layers that were interconnected using through-hole vias. The PCB material applied was a standard FR4 epoxy. Below the PCB a FR4 spacer layer and the ferrite layer were added.

10 Driver and Receiver Modelling

There are several circuit topologies available for the driver. The saturating class C is the easiest design consisting of a switch operating at the resonance frequency of the. The class D topology is a half bridge circuit, where does not necessarily operate at resonance. Both class C and D drivers offer a high efficiency. Class E is the most complex design, it operates at the resonance frequency and offers the highest efficiency, in particular for low magnetical coupling and high operating frequencies.

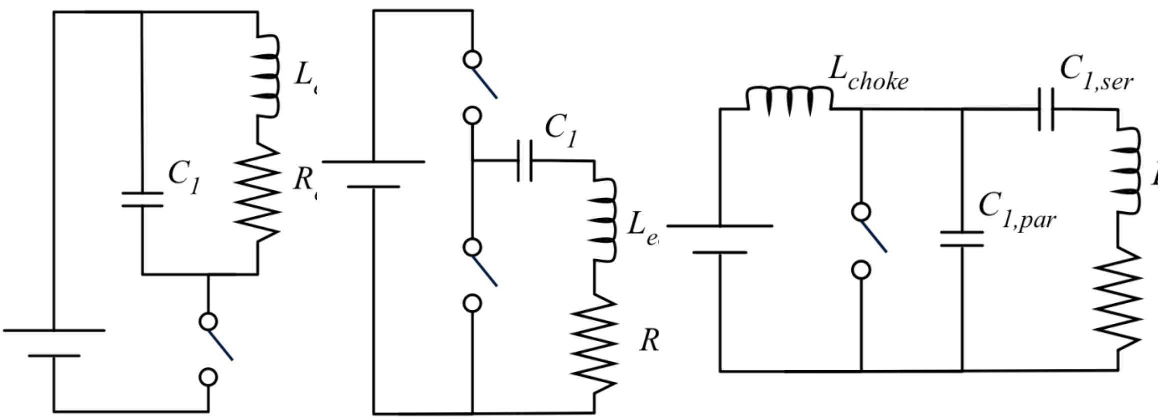


Figure 52 Driver circuit topologies (from left to right): Saturating class C, class D, class E

11 Driver and Receiver Realization

In order to test the results an inductively powered mouse was built. The mouse can be powers by regular moves of the mouse over the transmitter. The receiver was designed to fit into the battery compartment of the mouse that holds to AA sized batteries. The energy is buffered in the receiver in a super cap capacitor that can be charged quickly and has a long lifetime.

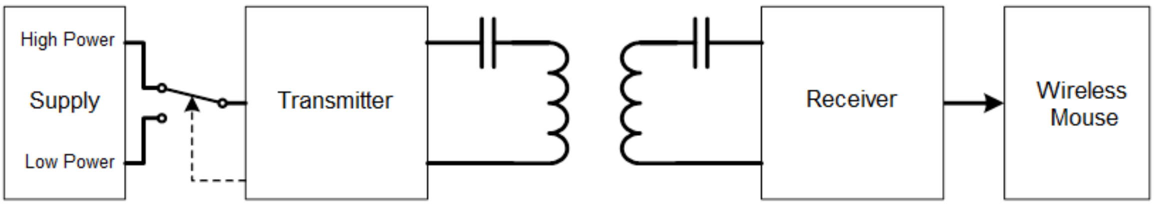


Figure 53 Block diagram of wireless mouse test case

Figure 53 shows the block level diagram of the charging system while figure 54 shows the secondary side including the flow of power from receiver coil to the mouse and the measurement of the charging status of the mouse the available energy in the buffer capacitor and transmission to the primary side using load modulation.

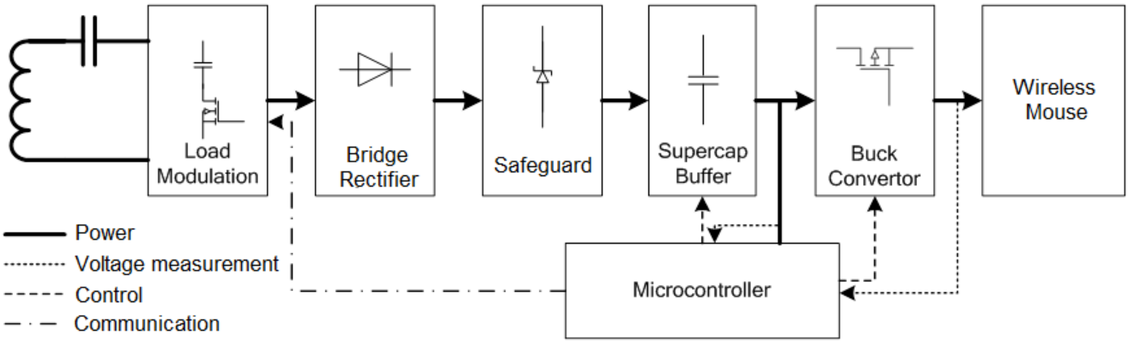


Figure 54 Block diagram of secondary side of wireless mouse

12 Dissemination of Knowledge

The technical and scientific results of the project have already been published in a scientific journal and presented on a conference:

- N. Stevens, B. Thoen: 'Shift of the quality factor frequency for inductive wireless power applications', Electromagnetic Compatibility (EMC Europe), 2014, International Symposium on
- N. Stevens, 'Normalisation of magnetic field distribution generated by circular current loop', Electronics Letters, Vol. 50, Nr. 17, 2014

Two additional publications in scientific journals are being planned:

- G. Fotheringham, J. Ventura, U. Maaß, B. Curran, I. Ndip, N. Stevens, D. Debouvere, B. Thoen: Planar Inductors for Wireless Power Transfer Manufactured Using PCB Technology
-

In order to disseminate the knowledge to companies it is planned to offer a workshop on the topic of the wireless charging. In addition it is planned to offer the knowledge as service to companies.

There have already been requests to use the design methodology introduced in the project to facilitate the realization of wireless power transmission.

13 Literature

[1] „http://www.wirelesspowerconsortium.com,“ [Online].

[2] S. S. Mohan, M. M. Hershenson, S. P. Boyd and T. H. Lee, "Simple accurate expressions for planar spiral inductances," *IEEE J. Solid-State Circuits , vol. 34, no. 10,,* pp. 1419-1424, Oct 1999..

[3] H. A. Wheeler, „Simple inductance formulas for radio coils,“ *Proc. IRE,* Bd. vol. 16, Nr. no. 10, p. 1398–1400, Oct. 1928.

[4] I. Bahl, Lumped Elements for RF and Microwave Circuits, Boston: Artech House, 2003.

14 Distribution of Tasks

The following table gives an overview of the contributions of the partners to the work packages.

WP Number	**WP Title**	**Contribution**
1	Technology and State-of-the-Art	KU Leuven, IZM
2	Determination of Required Inductance	KU Leuven, IZM
3	Coils in Substrate: Modelling	KU Leuven, IZM
4	Coils in Substrate: Realization	IZM
5	Ferrite in Substrate: Modelling	IZM
6	Ferrite in Substrate: Realization	IZM
7	Driver and Receiver: Modelling	KU Leuven
8	Driver and Receiver: Realization	KU Leuven
9	Integration of Driver and Receiver Electronics on the Substrate	KU Leuven
10	Guidelines for Optimized Design Cycle	KU Leuven, IZM

Appendix to Final Report
IGF-Project 92 EN WIPOS

1 BENEFIT FOR SMES 2

2 UPDATED PLAN FOR TRANSFER OF RESULTS 2

2.1 Specific Measures Implemented during the Project 2

2.2 Specific Measures to be Implemented after the Project 3

3 FEASIBILITY ASSESSMENT 4

4 SUMMARY / EVALUATION 4

5 OVERVIEW OF PERSONNEL AND OTHER EXPENSES 5

1 Benefit for SMEs

Mobile appliances for consumer applications such as laptops and phones have high demands on availability and mobility. Due to the size and weight of the batteries for the electronics a compromise between energy consumption and runtime has to be found in the design. In order to recharge the battery a connection to the mains supply is required which is commonly provided through a charger with cable and a specialized connector at the device. As the connectors at different mobile devices are often not compatible one has to carry several chargers which is an inconvenience. In addition industrial applications in explosive environments may prohibit the use of connectors due to the risk of arcing. Other applications, such as medical implants cannot be recharged by wire without discomfort or health risks for the patients.

A solution for the problem is the use of wireless charging by means of AC magnetic fields. The mobile devices are equipped with receivers to collect the energy from the magnetic field which is generated by the transmitter in the charging base station. This technology allows to eliminate the charging connector.

There are several standards already available that specify the various aspects of the charging, such as the electrical and geometrical specifications. In order for devices to be compatible with standards they have to comply with the specifications. While large companies are able to develop charging sub-systems, smaller companies often do not have the necessary engineering resources.

The goal of the Wipos project was to assist smaller companies by providing the necessary information to realize wireless charging systems. This includes details of the underlying physics, the electronic circuit design as well as the realization technologies. The results of the research were transferred into guidelines and software tools to support in the design and realization. In addition the design methodology was demonstrated using a charging system for a wireless mouse including a charging base station.

During the project the state of the art in the design of the electronic circuits and the realization of the coils for the transfer of the magnetic energy as well as applicable standards with respect to electrical functionality and safety were compiled. Using comprehensive simulation investigations design rules and guidelines were deducted. The results are readily accessible to design engineers in a software tool that allows for the design of wireless power system and the comparison of different realizations. The scientific focus of the project in terms of the realization was on the application of substrate integrated coils, their comparison to state of the art Litz wire coils as well as the design of large area transmitter coils.

Substrate integrated inductors allow for the optimization of the design towards application requirements, such as low profile charging systems, miniaturized or large area applications using standard PCB fabrication technologies. While the achievable inductance values are generally speaking similar to state of the art Litz wire coils the conductor losses are higher limiting the charging range. These results were presented at scientific conferences and in journals.

In addition to the project results that can be used by SMEs the knowledge generated during the project is available at the participating research centers and is offered as a service to the industry. This includes feasibility studies for the integration of wireless charging, design of systems and individual components as well as consulting services.

2 Updated Plan for Transfer of Results

2.1 Specific Measures Implemented during the Project

A) Project Website

Goal	Occasion	Date
Information of general public and experts on project	Specific information on project and its partners, contact information	Initial release July 2013, regular updates

B) Electronic Newsletter of FST2

Goal	Occasion	Date
Information of registered customers, project partners and other interested parties	Overview of project in SDI-Newsletter (approx. 300 subscribers)	July 2013

C) Annual Report FST2

Goal	Occasion	Date
Information of registered customers, project partners and other interested parties	Presentation of FST2 and project results	April 2015

D) Presentation of Project Results in Seminars, at Scientific Conferences and in Scientific Journals

Goal	Occasion	Date
Distribute project results to experts	Academic seminar at TU Berlin	April 2015
	Conference EMC Europe 2014	September 2014
	Journal Electronic Letters	August 2014

E) User Committee Meetings

Goal	Occasion	Date
Distribute and discuss project results with representatives from SMUs of user committee	Overview and discussion of project results	Sept. 2013, Dec. 2013, March 2014, June 2014, Sept. 2014

2.2 Specific Measures to be Implemented after the Project

A) Presentation of Project Results in Seminars, at Scientific Conferences and in Scientific Journals

Goal	Occasion	Date
Distribute project results to experts	Journal	Submitted
	Journal	Submitted
	Journal	To be submitted in Oct. 2015

B) Presentation of Project Results in Professional Magazines

Goal	Occasion	Date
Distribute project results to professional developers	Journal Elektronikpraxis	Approx. Oct. 2015

C) Presentation of Project Results in Workshop

Goal	Occasion	Date
Distribute project results to professional developers	Applications-specific workshops with industrial partners	Approx. End of 2015

D) Presentation of Project Results in SME Association Work Group Meeting

Goal	Occasion	Date
Distribute project results to professional developers	FE work group meeting	Approx. Sep. 2015

3 Feasibility Assessment

The proposed measures for the transfer of results to industry (especially SMEs) have been implemented as proposed. The project results required for the publication of scientific and professional journal papers are available at the research centers and some papers have already been published. The results will be edited in preparation of a workshop on the design of wireless power systems which will be offered starting at the end of the year.

However, the adoption of wireless charging into applications has been rather slow. This was also noticeable in the declining number of participants at the German UC meetings. This could be due to the fact that there are not many applications including wireless charging systems. It is hoped that by demonstrating more applications for wireless charging systems more developers will become aware of the technology and see the benefits.

4 Summary / Evaluation

The project Wipos was dealing with the realization of wireless charging modules. While state of the art realizations use Litz wire coils for the transmitter and receiver coils the scientific scope of the project was on the use of substrate integrated coils and its implications on the system design and electrical performance. Design methods for the transmitter and receiver electronics as well as substrate integrated coils were investigated. Using comprehensive electromagnetic field simulations electrical models were developed and implemented into design software tools. The models were validated using fabricated test structures and the design methodology demonstrated successfully on a wireless charging unit for a wireless mouse and a charging base station.

The results show that substrate integrated coils are comparable in terms of the required inductance to state of the art Litz wire coils while offering more freedom in the geometrical realization. This was shown e.g. in the analysis of large area transmitter coils that have been optimized with respect to the homogeneity of the magnetic field distribution. However, conductor losses in the metal traces are higher compared to Litz wire coils. This could be shown to be due to the parallel connection of individual wire strands in a Litz wire which is less affected by the resistance increase due to the skin effect. This concept could not be applied to substrate integrated coils with standard design rules leading to a reduced powering range between transmitter and receiver or, when compared to a charging system at the same powering distance, to an increase in charging time compared to state of the art Litz wire system. The project goal of designing electrically equivalent coils using planar technologies was therefore not achieved in all aspects.

The project results show that the technology has potential for applications with low power requirements and special demands regarding geometry and size. In order to transfer the results into product applications it is intended to submit a follow-up ZIM project. Initial feedback from SME companies have been positive.

5 Overview of Personnel and Other Expenses

WP1	Technology and State-of-the-Art	
Goal	Review of electrical, geometrical and safety related requirements based on a system-level analysis of wireless charging set-up as well as applicable regulations and standards. Definition of test cases for demonstration of project methodology.	
Results	Regulations, applicable standards, potential applications and current state-of-the-art was reviewed. Test cases and their requirements were defined. A system-level model of a charging system was developed.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 1	Fraunhofer IZM 0.5

WP2	Determination of Required Inductances	
Goal	Derivation of required electrical parameters (magnetic field strength, inductance, quality factors and magnetic coupling coefficients) from the system-level model. Definition of required electrical parameters for selected test cases.	
Results	Using the system-level model specifications for the test cases were derived. Substrate technologies were evaluated.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 3	Fraunhofer IZM 2

WP3	Coils in Substrate: Modelling	
Goal	Literature review of models for electrical properties of planar inductors without ferrite core. Modelling and of planar inductors and their coupling for wireless power transfer applications.	
Results	A patent review was conducted. A parameterized model for planar core-less inductors in different substrate technologies was developed and used to investigate the impact of fabrication tolerances.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 2	Fraunhofer IZM 5

WP4	Coils in Substrate: Realization	
Goal	Fabrication of test structures and sample planar inductors without ferrite core. Validation of electrical models from WP3.	
Results	The model was validated using measurements of test structures of planar core-less inductors.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 2	Fraunhofer IZM 4

WP5	Ferrite in Substrate: Modelling	
Goal	Analysis of electrical properties of ferrites suitable for integration into planar inductors. Review of models for electrical properties of planar ferrite-core inductors. Modelling of planar inductors and their coupling for wireless power transfer applications.	
Results	Electrical model for ferrite-core inductors was developed. Technologies for the integration were reviewed.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 6	Fraunhofer IZM 4

WP6	Ferrite in Substrate Realization
Goal	Fabrication of test structures and sample planar inductors with ferrite core. Validation of electrical models from WP5.

Results	Validation of ferrite core inductor models and comparison of core-less and ferrite core inductors.	
Completion of Goals	90%. Quality factor of planar inductors lower than state of the art due to limitations of the fabrication technology.	
Dedicated Personnel [PM]	KU Leuven DraMCO 1	Fraunhofer IZM 3.5

WP7	Driver and Receiver: Modelling	
Goal	Review of applicable circuit configurations, electronic device characteristics and available devices. Modelling of driver and receiver electronics, implementation into software tool. Initial design, manufacturing in standard PCB technology and test of electronics modules.	
Results	Model for driver and receiver electronics implemented in software tool.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 6	Fraunhofer IZM 1

WP8	Driver and Receiver: Realization	
Goal	Optimization and re-design of test case electronics based on standard PCB technology. Manufacturing and characterization of test cases.	
Results	Enhancement of software tool to include standard component models into software tool	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 6	Fraunhofer IZM 1

WP9	Integration of Driver and Receiver Electronics on the Substrate	
Goal	Design, manufacturing of substrates and assembly of components as integrated module. Complete electrical characterization and comparison to specifications as well as state-of-the-art systems.	
Results	> 100% Test cases manufactured with planar inductors, characterization and comparison to state of the art solution. Additional applications demonstrated.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 3	Fraunhofer IZM 2.5

WP10	Guidelines for an Optimized Design Cycle	
Goal	Edit knowledge gained in project to create comprehensive design guide for wireless systems. Finalize software tools.	
Results	Report on theory and design of wireless charging stations employing planar inductors, finalisation of software tool.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 4	Fraunhofer IZM 1

WP11	Dissemination of Knowledge	
Goal	Implement measures to distribute the knowledge to general public and specialists such as a website, conference papers, scientific journals and popular scientific magazines. Organize user committee meetings on a regular basis for presentation and review of the project results.	
Results	Publication of results using project web server, newsletter, publications of papers in scientific journals and on conferences.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 2	Fraunhofer IZM 1

WP12	Project Management
Goal	Organize regular information exchange between project partners using collaboration server and regular telephone conferences. Monitor the project progress and timely submission of deliverables to the funding agencies.

Results	Organization of collaboration between research agencies, research centers and user committee.	
Completion of Goals	All goals were fully accomplished.	
Dedicated Personnel [PM]	KU Leuven DraMCO 0	Fraunhofer IZM 0.5

KU Leuven / DraMCO and Fraunhofer IZM contributed 36 PM and 26 PM researchers respectively to the project resulting in a total of 62 PM. The researchers at IZM (income group TVÖD E13) were supported by student assistants for a total of 8.25 PM.

Expenses for investments included the purchase of a sample holder for magnetic materials that was used for the measurement of the magnetic properties of the ferrites for the ferrite core inductors and the test cases and an automatic measurement set-up for the characterization of the magnetic coupling factor between transmitter and receiver coils of wireless charging systems. The sample holder was used to determine the frequency dependent material properties of the ferrite to achieve a high modelling accuracy for the magnetic core inductors. The measurement set-up for the magnetic coupling factor was used to determine and optimize the magnetic field distribution of the coils.

Third party contracting was used for the manufacturing of some of the test structures that could not be manufactured in the research centers, mainly part of the air core inductors in PCB technology. This allowed for an assessment of standard manufacturing technologies in terms of electrical performance and cost.