Wireless powering of single-chip systems with integrated coil and external wire-loop resonator.

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A procedure for inductive wireless powering of single-chip systems is presented. An integrated spiral coil is used as the power receiving component. An external resonator formed by a wire-loop inductor connected to a capacitor is placed in close proximity to the chip. The sinusoidal magnetic field generated at a distant transmitting loop is amplified by the resonator. The present approach enables delivering power in the order of tens of microwatts to a few milliwatts at distances longer than 10 cm using a frequency of 13.5 MHz. The integrated coil used here can be fabricated with any integrated circuit fabrication technology.

Inductive wireless power transfer was demonstrated in the 19th century. Yet, contributions to the field are still appearing in the literature, which show potential for room size range wireless powering,[1] or sheet-type powering systems fabricated with low cost printing technologies.[2] The efficiency of inductive power transfer is not very high when the distance is larger than the size of the transmitting coil. However, since it provides a means for power supply without need of power cords or batteries, this technique is finding widespread application in small low power electronic devices such us access cards, radiofrequency identification tags, and wireless sensors. The general trend is to integrate as many possible components of the systems into a single chip. Typically for this integrated solutions, the chip is connected to an external coil through which the power is received. There are a number of reasons for trying to integrate also the coil and produce monolithically integrated systems. Low cost applications could benefit from this integration since most of the cost of current devices is associated with the process of connecting the chip to the external coil.[3] Reliability could also be improved, especially for systems working in a wet environment.[4] However, integration of the receiving coil implies a decrease of coil area and quality factor that severely limits the maximum working distance of the wireless systems. Fully integrated systems proposed so far are designed for distances ranging from 1 to 3 mm.[5,6]

In this letter we propose a procedure for wireless powering of single-chip systems that combine the cost and reliability advantages of fully integrated systems with the longer working range of external coil systems. Figures 1.a and 1.b show a schematic representation of the proposed system and its equivalent circuit, respectively. The chip is attached to a holder piece that contains a single loop inductor-capacitor (LC) resonator, but it is not connected to it. A distant transmitting loop generates a varying magnetic field that produces an electromotive force (V_{emf}) at the resonator loop. The current trough the loop is amplified by the resonance and generates a much

larger magnetic field than the original one. This wireless power transfer approach is similar to the one proposed by André Kurs *et al.*[1] for larger dimension devices. They achieve high power transfer efficiency by working in the strong coupling regime, that is, by ensuring that $k^2 Q_T Q_R > 1$ where k is the coupling coefficient between the transmitting loop and the resonator, and Q_T and Q_R are the quality factors of the transmitting loop and resonator, respectively. In the application presented here quality factors and coupling coefficient are much lower due to smaller dimensions of the resonant elements. This prevents working in the strong coupling regime. Nevertheless, the use of a resonant element close to the monolithically integrated system greatly increases the voltage and power picked up by the on-chip coil.

The integrated coil used in this work was an aluminum 20 turn square spiral inductor with 3.5 mm side for the outer turn and 2.5 mm side for the inner turn. The fabrication was carried out by common photolithography and etching techniques on a 0.7 Ω·cm p-type silicon wafer with a 2.0 μm-thick thermally grown silicon oxide layer and a 3 μm-thick aluminum layer deposited by sputtering. The inductance and series resistance measured at 13.5 MHz were 1.8μH and 220 Ω, respectively, which yields a quality factor of 0.7. The selfresonant frequency was 34.2 MHz, much larger than the target operation frequency (13.5 MHz). An integrated coil with similar parameters could be fabricated using any of the current commercial CMOS (Complementary Metal-Oxide-Semiconductor) technologies. The coil chip was glued and wirebonded to a printed circuit board with minimal dimensions to avoid additional magnetic coupling to its copper tracks. Three square loop resonators with side lengths of 1.25 cm, 2.5 cm and 5.0 cm where tested. The resonators where made with 1 mm-diameter cooper wire connected to chip capacitors (Murata GRM40 series) whose values where chosen to yield 13.5 MHz resonant frequency. The power transmitting loop was 10 cm in diameter and was formed with 1 mm copper wire. The

transmitting loop was also made to resonate at 13.5 MHz by connecting a tuning capacitor in parallel. A function generator (Agilent 33250A) with a smaller loop coupled to the transmitting loop was used to drive it in resonance. The sinusoidal voltage at the transmitting loop was measured to be 17.5 V amplitude throughout the experiments. This translates into a 0.7 A amplitude current for a reactive loop impedance of 25 Ω at 13.5 MHz. The voltage across the integrated coil was measured with a Yokogawa DL 9140L oscilloscope and 10x probes (16 pF and 1MΩ input impedance). Direct coupling from the transmitting loop to the oscilloscope probe and connection wires was measured to contribute less than 10 mV.

Figure 2 shows results of the voltage obtained for the 2.5 cm side resonator with two different load resistances that emulate two system power consumptions. A curve for the case of no load is also shown. In order to maximize the coupling, and hence the transmitted power, the integrated coil was placed underneath the resonator wire as shown in Figure 2 inset. Power delivered to the 220 Ω load resistors for the three resonator sizes is shown in Figure 3. The power values where calculated from the measured voltages at the load resistor.

Theoretical values of voltage and power at the load resistor are also shown in Figures 2 and 3. Calculations of the voltage amplitude measured at the load resistor were carried out using the equation

$$V = \frac{\omega_0^2 M_{RC} \, B \, l^2 R_L}{R_R \left(R_C + R_L\right) + \omega_0^2 M_{RC}^2} \tag{1}$$

derived from the equivalent circuit in Fig. 1.b, where ω_0 is the radian resonant frequency, l is the side length of the square shaped resonator, B is the magnetic field amplitude, M_{RC} is the mutual inductance between resonator and integrated coil, R_R is the series resistance of the resonator, R_C is

the series resistance of the on-chip coil, and R_L is the resistance of the load. Here we assume that a capacitance C_C is placed in series with the on-chip coil to cancel out its reactive part and maximize the received power. The analytical solution for the magnetic field, B, along the axis of a circular current loop is well known[7]. We have not tried to obtain an analytical expression for R_R because the contribution to the resonator losses come not only from the copper wire, but from the chip capacitors and the solder paste. Instead, the values used in the calculations were obtained from the resonators quality factor with the formula $R_R = \omega L_R / Q_R$. The resonators quality factor was measured with the Agilent 4395A network analyzer, yielding 116.4, 106.4, and 87.5 for the 5 cm, 2.5 cm, and 1.25 cm side lengths, respectively. The mutual inductance, M_{RC}, was calculated using the method by Grover,[8] which is based on the exact solution for the mutual inductance of two parallel conductors.

The results shown on Figure 3 demonstrates that the present power transfer approach enables delivering power in the order of tens of microwatts to a few milliwatts at distances longer than 10 cm to a fully integrated system coupled to (but no connected to) an LC resonator having dimensions smaller than a typical credit card. The theoretical values calculated with Equation 1 show a good match with the experimental results.

The geometry of the elements used in this work was kept simple to allow an easy proof of concept and analytical description. The received power can be further increased by, for example, increasing the mutual inductance between the chip and the resonator loop, or by increasing the quality factor of the LC resonator. It is important to note also that the electromagnetic fields generated by the transmitting loop are below the limits fixed by the Institute of Electrical and Electronics Engineers (IEEE) regarding safety levels,[9] or the Federal Communications Commission (FCC) regarding electromagnetic compatibility.[10]

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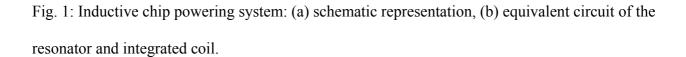
Fig. 1: Inductive chip powering system: (a) schematic representation, (b) equivalent circuit of the resonator and integrated coil.

Fig. 2: Voltage at the load resistor versus distance with the 2.5 cm side resonator for resistive loads of 220 Ω (triangles), 1kΩ (circles), and no load (squares). Calculated values are shown as doted, dashed and continuous traces, correspondingly. Inset shows the position of the chip relative to the cooper wire loop.

Fig. 3: Power dissipated at the load versus distance for resonators with side length of 1.25 cm (triangles), 2.5 cm (circles), and 5 cm (squares). Calculated values are shown as doted, dashed, and continuous traces, correspondingly.

(a) *LC* resonator

$\vec{B}$

Integrated coil

Transmitting loop

(b)

$V_{emf} = \omega BA$ C_R R_R M_{RC} R_C C_C

L_R L_C R_L