Inkjet Printing of Structures for MRI Coils

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Abstract

We present the characterisation of inkjet printed conductive tracks and capacitors. The target application is the fabrication of inductors with built in capacitances for an application in Magnetic Resonance Imaging (MRI). The resonance circuit consists of three components : restive parts R[Ω], inductive ones L[H] and capacitive ones C[F]. These form a resonance circuit with a resonance frequency adjustable to the target value of 400 MHz. The fabrication of the R and C components are discussed in this paper. Due to the special environment for which the circuit is aimed for, both the substrate and the coils must be free of ferromagnetic materials. To get more flexibility with regard to the spatial application of the coil, the system should be flexible so that it can for example form a tube. Therefore a variety of these components have been produced on a flexible Kapton substrate. Kapton not only has the advantage that it can be obtained as very thin foils (< 20 µm), but it is thermally stable (up to over 300°C). Colloidal silver ink was used as conductive material. To cure the silver ink temperatures below 300°C were needed. Aiming for a resonance frequency as high as 400 MHz resulted in fairly small and therefore easy producible values of C and L. R is only an unwanted component in the circuit, it should be as small as possible. The skin effect which describes the conductive layer thickness in a bulk conductor at high frequencies, reduces this conductive layer. Therefore only a few µm thick conductive domain is participating in the conduction. To achieve such a thickness by printing, only a few layers of ink are needed. The components have been measured and analysed with regard to linearity.

Introduction

Over the last few years inkjet printing has been transformed from a purely graphical output producing technique to a versatile production method. To give two examples it is used now in the field of biology, to deposit cells [1] and in the field of electronics to print polymers with semiconducting properties, to produce transistors[2], diodes and displays[3]. To get flexible displays, the tracks also need to be flexible. The most similar application to the one presented in this paper, was the printing of Radio Frequency Identification resonant circuits (RF-ID) [4]. The resonance frequency of these RF-IDs is at 13.56 MHz.

We present the first results of inkjet printed conductive circuits for receiver coils in magnetic resonance imaging (MRI). In an MRI machine there are large superconductive coils that create a homogeneous B_0 field of ~1 Tesla. To keep the nuclei spins in precession an RF-B-field B_1 with µT-strength is overlayed [5]. The developments in MRI are continuously going towards higher field strengths. Current scanners for human diagnostics are operated at a field strength of 1.5 Tesla or 3 Tesla. Animal scanners are operated up to 9.4 Tesla.

The field strength defines the resonance frequency and therefore has a great influence on the design of the receiver coils. The resonance frequency of the coil must be tuned to the precession frequency (Larmor frequency) of the targeted spin carrying nuclei. For hydrogen the Larmor frequency ω_H is

$$\omega_H = 42.58\,\frac{\mathrm{Hz}}{\mathrm{T}} \tag{1}$$

Our target application is a 9.4 Tesla machine, so the desired resonance frequency is 400 MHz. The spacial encoding which enables real imaging is also obtained using this field strength dependency of the frequency. A linear gradient in the magnetic field is superimposed. By doing so the position is encoded into the frequency domain [5].

The needed components of a resonating LC circuit at a frequency of 400 MHz can be obtained using the well known formula 2[6].The resulting values have fairly small values and are shown in Figure 1.

$$400\,\mathrm{MHz} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

L and C influence the resonance frequency in the same way. Therefore there is an infinite number of possible combinations. Due to producibility the following values are a feasible tuple.

$$L = 160\,\mathrm{nH} \tag{3}$$
$$C = 1\,\mathrm{pF} \tag{4}$$

These values can be achieved in a planar arrangement. The resistance of the track comes into account only as damping; it should therefore be as small as possible. This paper only presents measurement data for the resistances and the capacitance. The inductance is created by the geometrical form of the printed tracks, this part will no further be discussed in this paper.

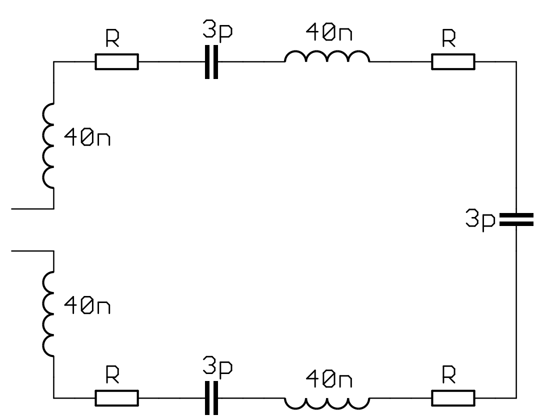


Figure 1. *Schematic of a resonant RLC circuit*

For the calculation of a capacitance the dielectric constant of the material ε_r, the area of the opposing conductive layers and their distance are needed. The goal is to built the resonance circuits on a flexible substrate, therefore the substrate needs to be fairly thin, but not too thin, because otherwise it is not mechanically stable. In this case we choose 50 µm Kapton (Polyimide) foil, which on account of its thinness could be directly used as the dielectric for the capacitance. Using the equation for plate capacitance and choosing the variables from our setup

$$C = \frac{\varepsilon_0 \varepsilon_r}{d} A \quad (5)$$

$$d = 50\,\mu\text{m} \quad (6)$$

$$\varepsilon_r = \sim 3.4 \quad (7)$$

we get the following capacitance density

$$C(A) \approx 0.6 \frac{\text{pF}}{\text{mm}^2} \quad (8)$$

For the conductive tracks, the fact that the circuit is operated at a frequency of 400 MHz must be considered. Inkjet printing has the advantage that it deposits small droplets ($\sim 50\,\mu$m) with a high lateral accuracy. But using small droplets, leads to fairly thin layer thicknesses of ~20 µm for the wet ink. As the used inks had only a solid fraction of 20 wt%≈ 2 vol%, the resulting layer thickness was ~500 nm. To build up thick conductive layers is possible, but takes a lot of time The advantage at 400 MHz, is the fact that the current is not conducted in the bulk of the conductive track, but only in the outer skin. The effective depth in the conductor where the current flows is the so called skin depth, which can be calculated by the following formula [6]:

$$\delta = \sqrt{\frac{2\varepsilon_0 c^2}{\sigma 2\pi f}} \quad (9)$$

With the values for the conductivity σ of the used silver ink and the frequency f of 400 MHz

$$\sigma = \rho^{-1}\Omega\text{m} = 10^7 \frac{1}{\Omega\text{m}} \quad (10)$$

we get a skin depth of

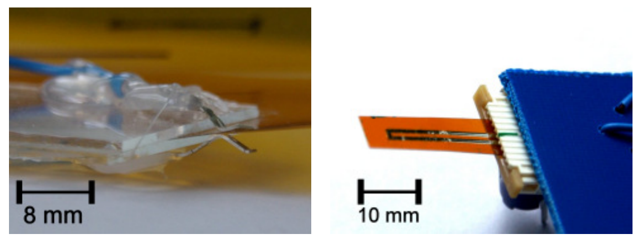
$$\delta = 7.96\,\mu\text{m} \quad (11)$$

Having a planar conductor width (w) >> thickness (t) the conductivity at the sides can be neglected. For the top and bottom side only 8 µm are conductive, therefore the maximum needed track thickness is 16 µm.

Experimental

To compare the values calculated using formula 8 with the values of an inkjet capacitors a test series have been printed for the capacitors. Square capacitors of different sizes ranging from 9 mm² to 100 mm² have been produced and measured. For the printing process two devices were used. First, a Dimatix s-2800 (FujiFilm Dimatix Inc., Santa Clara, CA, USA), with a 16 nozzles piezo printhead. The second printer was an in-house made device [7]. The in-house system used a piezo driven printhead with an 80 µm nozzle (MJ-AT-080, MicroFab Technologies Inc., Plano, Texas, USA). The ink in both systems was a silver nano powder produced by SunJet (SunJet, Bath, UK). The U5603 Ink had a silver content of 20 wt% and a resistivity of $\rho = 5 - 30 * 10^{-8}\,\Omega$m for the sintered ink. To get a uniformly closed film for the capacitive plates, two layers were printed on each side of the Kapton substrate. Two layers were printed on one side of the substrate, then heated to 220°C to evaporate the solvent in the ink and to sinter the silver. The substrate was put back in the printer and was aligned with the help of a camera. Then the two layers for the second plate were printed. The substrate was put again on the hot plate and left there for 5 min to get well-sintered areas.

To connect to the two-sided capacitance test structures a custom-made two tip setup shown in Fig. 2.a) was used because the printed layers were too thin to solder on them.



(a) Connecting tipps for Capacitance (b) Clamp for flexible substrate

Figure 2. Connection devices for R and C

The values of the capacitance were measured using an RC element and an oscilloscope (Figure 3). The oscilloscope added a capacitance of 13.46 pF parallel to the test structure. This value was subtracted from the measured results.

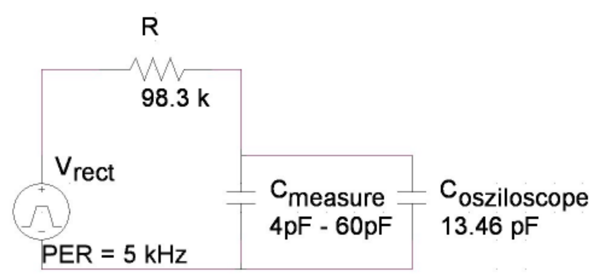


Figure 3. Measurement setup for the capacitance

The properties of the capacitance and the resistive tracks can be tuned individually. The value of the capacitors can be tuned by varying the overlap area. The value of the resistance depends on the tracks cross-sectional area and therefore the thickness of the tracks is crucial. To characterise this property, conductive tracks with an increasing number of layers ranging from 1 to 20 layers have been printed using the Dimatix printer. For the resistive test structures, as for the final coils, mechanical squeezing clamps, as shown in Fig. 2.b), had been used. These clamps are standard connectors for flexible substrate cables.

Due to the limitation of the connector clamp the start and the of end conductive track needed to be next to each other, so that the conductive tracks always formed a U -shaped coil and therefor an inductance. The resistance measurements have therefor only be done DC. An analysis of the AC behaviour needs to be done on the way of getting the final coils.

As the connector clamps will be used for the final coils, both ends of the coil need to be on the same side of the substrate. For the final coil setup this problem will be circumvented by choosing an even number of capacitors. Using 2^n capacitors for the final coil, the track going to the connector from the last capacitor will always be on the same side as the one going to the first capacitor.

Results and Discussion

With a profilometer, the thickness per layer was measured as being ~500 nm. The problem was that the used Kapton had no optical quality and therefore its roughness was also in the region of several hundred nm. After the first layer the track was not homogeneously covered. The situation got better from layer to layer, after three layers the complete track area was always covered.For the resistance the number of layers were the dominating term, the resistance scaled nearly linearly with the number of layers, as shown in Fiq. 4.

Nevertheless there is a difference in the way the tracks were printed and sintered. From Layer 1 till layer 4 the tracks where sintered directly after printing each layer. For the layers 8-16 they had only been sintered after printing 4 layers. The fit lines through the regions show a significantly different slope. For the directly sintered region (represented by the dashed line) the increase in conductivity is $0.1\,\Omega^{-1}$ per layer, for the four layer one sinter step region (doted line) it is only $0.05\,\Omega^{-1}$ per layer. Therefore it is advisable to sinter the tracks after each layer. Layers 4 to 8 where sintered after each second layer and they also showed a reduced increase of conductivity per layer compared to the first 4 layers, this fit was left out to prevent the graph from being overloaded.

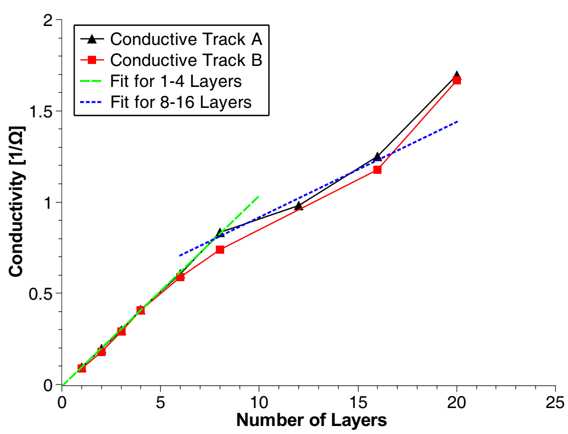


Figure 4. Conductance of printed 2 conductive tracks from 1 to 20 layers

For the capacitance only two layers were used. Even though one layer would be enough per side for the capacitance, two were chosen, to prevent the inhomogeneities describe before for the single layer tracks. Measuring the capacitance with the described RC element (Figure 3) gave the values plotted in Fig 5. The values for square capacitance were measured from 9 mm² to 100 mm².

So both the resistance and the capacitance scaled linearly with the number of layers and the overlap area of the plates respectively. A schematic of a possible resonant circuit using the achievable values for C and R is shown in Figure 1. Simulations had shown that a distribution of capacitance over the coil loop improved the homogeneity of the currents in the circuit. The pair

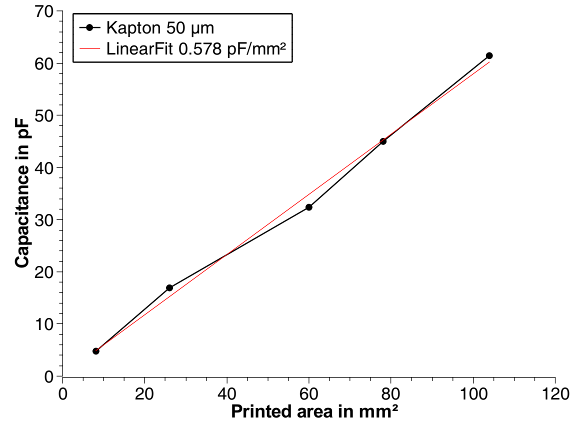


Figure 5. Values of printed capacitance with a square area from 9 mm² to 100 mm²

values which gave a resonance frequency of 400 MHz are listed in Eqn. 3 and Eqn. 4. As three capacitors were connected into series, each of the capacitor needed to have the triple value of 3 pF to get a total capacitance of 1 pF.

Conclusions

We analysed the R and C components of a resonance circuit. C is needed to make a resonant circuit, therefore it should be produce very accurately. R should be as small possible. Both types of electrical components could be produced in a way that they scaled nearly linearly with an input value (thickness, overlap area). The design of the components was chosen in the way that it met the requirements imposed by the later application like, being compatibly with a high magnetic field and single side contacts on a flexible substrate.

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Dario Mager obtained his Diploma Degree in MEMS-Technology at the Department of Microsystems Engineering (Freiburg, Germany) in 2004. In his thesis he simulated CMOS based piezo resistive stress sensors. Since 2005 he his working on his PhD Thesis in the Laboratory for Simulation at the same institute. He is using Inkjet Printing techniques to develop new Rapid Prototyping devices and to print MRI coils.