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Inkjet Printed Micro Saddle Coil for MR Imaging

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Abstract

This paper demonstrates novel approaches to fabricate micro-scale saddle coils via a combination of rolling-up of thin polymer films [1, 2] and ink-jet printing technique. The printed conductive patterns can be directly electroplated, allowing for better conductivity and less signal loss for high frequency applications. To roll up 3D structures starting from 2D planar patterns, two methods were investigated. The performance of rolled-up coils were tested in a 500 MHz *spectrometer and an MR image of a water-filled capillary was successfully acquired.*

Introduction

Nuclear Magnetic Resonance Imaging (MRI) has become one of the most versatile non-invasive and non-destructive imaging techniques by reason of no ionizing radiation being used during a measurement. The information collected during MRI measurements is created by picking out the induced signal of spin magnetisation that is precessing in an external magnetic field. One of the factors that limit the spread of NMR is the sensitivity of the NMR probe, especially when dealing with low sample volumes or small masses (µl or µg). It has been shown that the performance and signal to noise ratio (SNR) of a probe can be significantly improved when its size is shrunk (diameters ≤1 mm) [3]. The relationship between SNR and the geometry of a solenoid and saddle coil is given by equation (1) and (2) respectively [4],

$$\Psi_{\text{solenoid}} \propto 0.29\mu_0 V_s/a \quad (1)$$

$$\Psi_{\text{saddle}} \propto 0.094\mu_0 V_s/a \quad (2)$$

where

Ψ: Signal to noise ratio available after a 90° RF pulse;

μ_0: Vacuum permeability, $4\pi \times 10^{-7} H \cdot m^{-1}$;

V_s: Sample volume in m^3;

a: Coil radius in m.

It is clear from the equations that, in dealing with the same limited sample volume V_s, the sensitivity of a detector coil inversely scales with its diameter. In addition, solenoid coils have better sensitivity than saddle coils with similar dimensions (equations 1, 2). On the other hand, a saddle coil construction has the advantage of being operated in the parallel direction of the B_0 field, thus causing less B_0 field distortion, which makes it easier to achieve high spectral resolution.

Unlike macroscopic NMR probe designs, many of the popular micro-coil designs are complicated and challenging to manufacture, mainly due to the difficulties in handling conductive structures at small dimensions [5, 6]. Therefore, planar coils and solenoid coils are the more common forms used for designing micro-coils [7]. While the manufacturing of solenoid coils can be done by directly wrapping copper wire around a cylindrical supporting structure [8], micro saddle coil construction still remains a challenge to fabricate.

Inkjet Printing

Beside its usage in graphical printing, inkjet printing has grown into a mature technique for depositing functional materials [9, 10], thanks to its flexibility and ability to precisely position materials through computer control. It has also been adapted to the field of printed electronics. Electronic components like conductors, capacitors, and transistors, have been successfully printed [11, 12]. Compared to conventional micro-fabrication methods, printing is a more convenient and cost friendly alternative to fabricate micro-structures, for the reason that no masks are required. In addition, drop-on-demand ensures that minimal amounts of material are consumed, and barely any waste is generated. Given the available technology, the resolution of inkjet printing is not as high as lithography techniques, due to the limitation of possible droplet sizes. However, it has been proven that this technique is more than sufficient to fabricate fine conductive patterns and MR applications [13, 14, 15].

One of the limitations of directly inkjet printing conductive patterns comes from the low sample volume deposited, which results in exceedingly thin metal layers. All the patterns reported in this paper were printed using a commercial FUJIFILM Dimatix DMP-2800 printer. The printer was equipped with an ink cartridge, which ejects droplets with a volume of 10 pL (DMC-11610, FUJIFILM Dimatix). The silver nanoparticle ink Suntronic U5603 (metal load 20 wt %) was obtained from Sun Chemicals. With a dot spacing setting of 25 µm, a single inkjet printed track line is around 50 µm wide and less than 500 nm thick [16].

Skin Effect

Due to the insufficient thickness of the directly printed silver tracks, the structures have very high RF resistance, which directly results in more noise during signal transfer. At low frequencies, the charge carriers transport through the entire cross-section of the conductor layer. By contrast, at high frequencies, the charge carriers can only pass through small proportion of the cross-section of the conductors, due to the radio-frequency skin effect [17]. The effective resistance increases greatly compared to when operated at low frequencies. The depth position at which the current density drops to $1/e$ of the value at the surface of the conductor, is defined as the skin depth δ_{RF}. The higher the working frequency is, the lower is the corresponding skin depth of a given metal. The goal of our work is to built micro saddle coils for an 11.7 Tesla NMR scanner, which has a working frequency of 500 MHz for the ^{1}H-channel. At 500 MHz, skin depths of common non-magnetic metals are around a few µms (Table 1). It is recommended that the thickness of the conductive layers is at least $2 \times \delta_{\text{RF}}$. A further increase of the layer thickness will not improve the conductivity significantly.

One direct approach to achieve thicker layers is through multi-layer printing. Several layers of the same pattern will be sequentially printed. However, this procedure is time consuming, especially for large patterns. The printing resolution also worsens, caused by the spreading of the jetted ink. A better method is to use the initially printed pattern as a seed layer for subsequent electroplating. One obstacle to direct electroplating onto inkjet printed patterns is the poor adhesion between the printed pattern and the substrate material. It has been shown [15] that this problem could be solved by both controlling the sintering temperature and the electroplating rate. The possibility to directly electroplate the printed patterns helps to reduce the fabrication time greatly and makes it easier to adapt the inkjet printing technique to high frequency application designs.

Skin depth of common non-magnetic metals at 500 MHz.

Metal	Skin Depth [μm]	Desired layer thickness [μm]
Gold	3.37	6.74
Silver	2.83	5.67
Copper	2.92	5.83

Fabrication

In this paper we report on micro-saddle coil patterns manufactured onto two types of transparent substrates: the stretchable Polydimethylsiloxane (PDMS) film (15 μm), and the stiffer 25 μm Kapton sheet (Dupont). Specifically designed 2D patterns were first inkjet printed on top of the substrates and afterwards carefully sintered at 200 °C to 250 °C to achieve minimal conductivity of the thin tracks ($t < 500$ nm). Instead of printing multiple layers, the samples were then electroplated with 5 μm gold. Micro saddle coil structures were obtained by rolling the finished planar patterns together with the underlying polymer film around a glass capillary tube (⊘ 600 μm), based on the rolling methods described below.

Assisted rolling process for PDMS substrates

PDMS, also referred to as silicone, was used as one of substrates because it is sufficiently flexible, optically clear, and non-toxic. The detailed fabrication steps are depicted in Figure 1.

a. The process departed from coating the glass carrier slide with a thin layer of Poly(4-vinylpyridine) (P4VP) (2 wt % in chloroform solution), which serves as a sacrificial layer and allows easy peeling of PDMS from the glass substrate.
b. 15 μm PDMS (Sylgard 184 silicone elastomer kit, 10:1 mixing ratio) was then dip-coated on top and cross-linked by thermal treatment (80 °C for 1 hour).
c. After using O_2-plasma to reduce the hydrophobicity of the PDMS surface, a thin layer of chitosan (< 1 μm, 1wt% in DI water solution) was dip-coated to around $4/5$ of the substrate as an intermediate layer for printing. Part of the PDMS film was left exposed for bonding with capillary tube later.
d. After the sample dried up at room temperature, the boundary area was carefully removed with a blade, to eliminate the uneven regions generated during the dip-coating process.
e. The prepared substrate was baked at 200 °C for 30 min, in order to further improve the wetting behaviour of the surface. The calculated coil pattern, including contact pads, was then inkjet printed on the Dimatix, equipped with a cartridge filled with Suntronic U5603 silver nanoparticle ink. To achieve printing at high resolution, all the printing tests were carried out in a single nozzle jetting mode with a 25 μm dot spacing setting (Figure 2 (a)). The width of the line tracks was set to 100 μm. Afterwards, the sample was first dried at 100 °C and then sintered at 200 °C for 10 min, which rendered the tracks conductive.
f. The electroplating was done in an industrial quality electrolyte ($K[Au(CN)_2]$) bath, with a pH of 6.5. 5 μm gold was electroplated at a speed of around 5 μm per hour (Figure 2 (b)). The residues were rinsed off in DI water for 30 min prior to further experiments.
g. After drying the sample gently with a compressed air gun, a glass capillary tube (⊘ 600 μm) was aligned and bonded to the exposed PDMS area by covalent Si-O-Si bond formation, after oxygen plasma treatment of the surface of the PDMS substrate and the capillary tube.

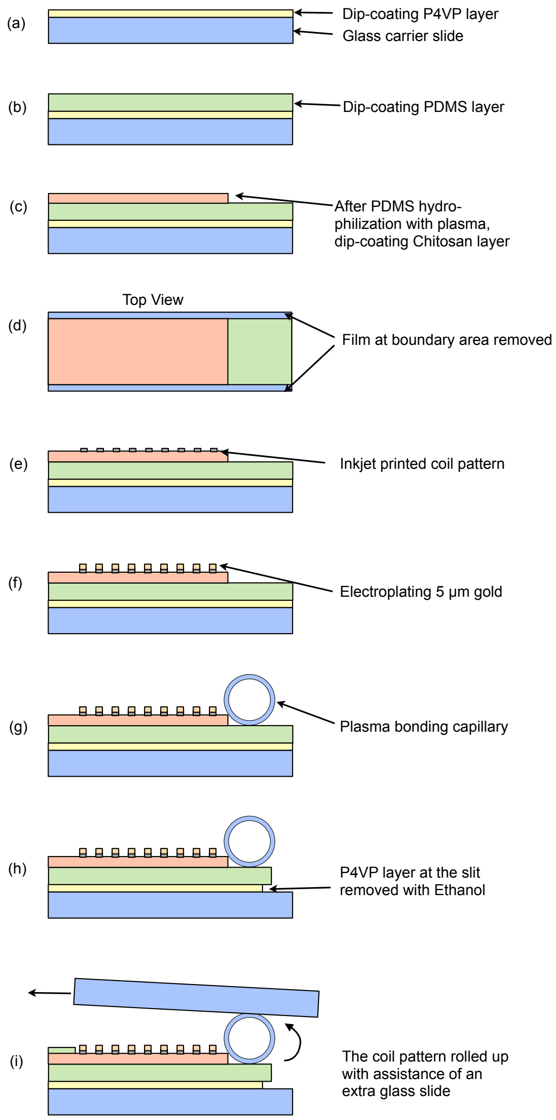
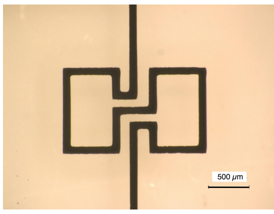
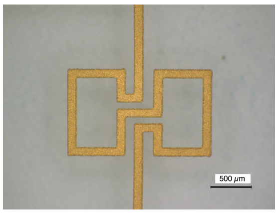


Figure 1. *Fabrication steps of the assisted rolling process based on PDMS substrates. (a-d) Coating and preparing the multi-layer substrate. Figure (d) is a top view. (e-f) Patterning with inkjet printing and electroplating. (g-i) Fixation of the glass capillary and rolling up the coil pattern.*

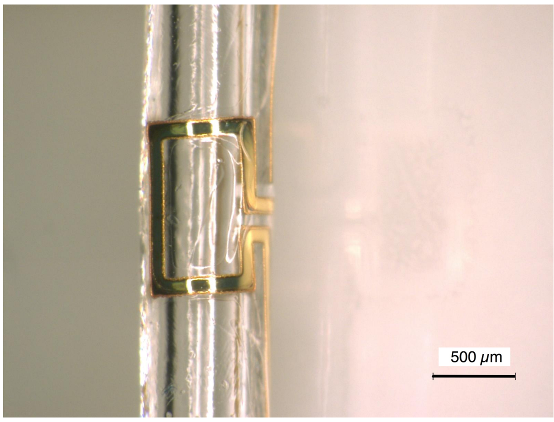
h. The film behind the capillary was then carefully removed with a blade. A few droplets of Ethanol was used to dissolve the P4VP layer at the slit opening. This extra step improves the coherence of the peeling process along the capillary.
i. Finally, an extra glass slide was placed on top of the tube, which was then pressed and pushed forward at the same time, while the substrate film was slowly peeled off from the glass substrate. The rolled-up structure was fixed by applying a thin strip of PDMS across the coil pattern and crossed-linked at 80 °C for a few minutes (Figure 2 (c) (d)).



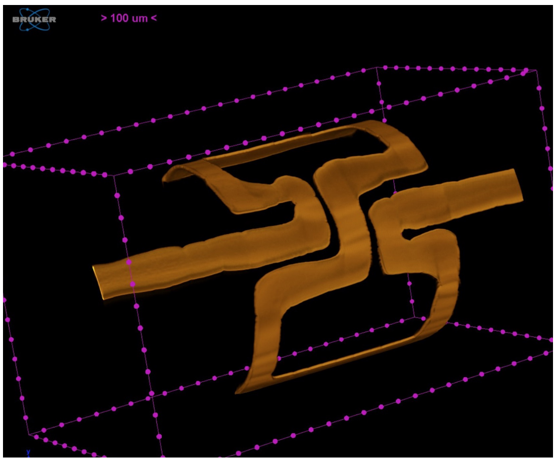
(a) After printing.



(b) After 5 µm electroplating.



(c) After rolling.



(d) MicroCT image of the coil.

Figure 2. 2D coil pattern deposited on top of a PDMS-Chitosan substrate. (a) The printed pattern looks smooth on the thermal treated Chitosan surface. The track width is 100 µm. (b) After being sintered at 200 °C, the adhesion between the printed silver track and Chitosan layer is sufficient for a direct electroplating process. (c) The rolled-up saddle coil exhibits great optical clarity. (d) X-ray CT of the final rolled coil acquired on a Bruker 1172 system at 100 KeV.

The finished coil remains on top of the glass slide and offers great optical transparency to the coil volume. The supporting glass capillary serves as an accommodation for the measurement solutions as well. Connections to external circuit can be achieved using conductive silver paste.

Assisted rolling process based on a Kapton substrate

The other approach relies on commercially available 25 µm Kapton film (Dupont). Kapton, which is one class of polyimide, is well known for its excellent mechanical and electrical properties. Even thin films are robust and exhibit very good chemical resistance. It has been widely used for manufacturing flexible printed circuit boards.

The as-received film was first cleaned with Acetone, Isopropanol, and DI water, always in an ultrasonic bath. The coil pattern was inkjet printed using the same processing parameters as discussed above for the PDMS-Chitosan substrate. The printed sample was then sintered at 250 °C for 10 min. After slicing into proper size, the sample was fixed onto a glass slide with PET tape, which was then electroplated inside the gold electroplating bath to a layer thickness of 5 µm. A rolling device, developed in house by Dr. Harald Vogt [18], was used to assist the rolling process of the Kapton sample. In the end, the rolled up saddle coil was fixed with a small amount of transparent glue (Der Alleskleber, UHU) (Figure 3).

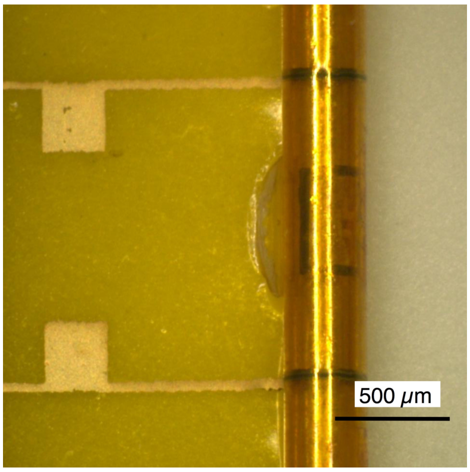


Figure 3. A saddle-coil based on a Polyimide substrate rolled up around a 600 µm capillary tube. The coil is 1 mm long and connected to an external circuit through contact pads (200 µm × 200 µm).

Measurement

The Kapton based micro saddle coil was fixed onto a printed circuit board (PCB) and connected to the electrical tracks using conductive silver paste. Afterwards, the setup was mounted onto a custom-made sample holder, designed to fit onto a commercial Bruker Micro 5 Probe base (Bruker). With a network analyzer (Agilent, E5071B), the coil was tuned to 500 MHz and matched to 50 Ω. The resonance was determined by measuring the transmission loss (S_{11}), and the quality factor was evaluated from the width at the -3dB level of frequency response as $Q = 2\omega_0/\Delta\omega_{-3dB}$ [19], giving a quality factor $Q = 23$ (Figure 4).

The glass capillary with an inner diameter of 150 µm, which accounts for less than 0.1 µl of the coil's inner volume, was filled with DI water using capillary forces. An MR image with

3 mm × 3 mm field of view (Figure 5) was successfully acquired in an 11.7 T spectrometer (Bruker, Avance III) using a 600 G cm^{-1} A^{-1} gradient system (Bruker Micro 5).

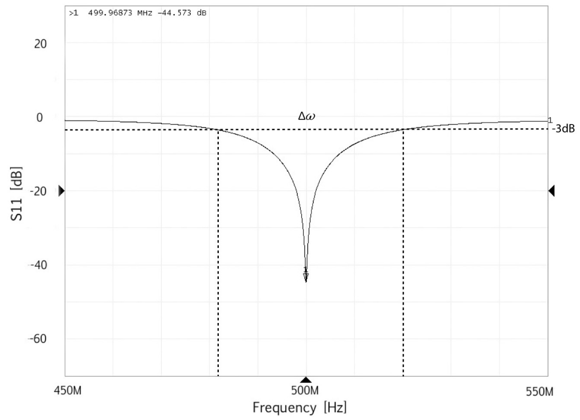


Figure 4. The reflection coefficient S_{11} measured to be around -44.5 dB, when the coil was tuned to 500 MHz and matched to 50 Ω. The resonance width at -3 dB was measured to be $f_{-3dB} = 43.5$ MHz, yielding $Q = 23$.

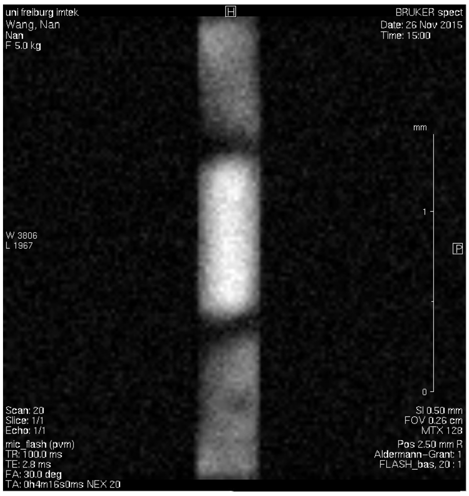


Figure 5. MRI of a DI-water-filled capillary with an in-plane resolution of 20 µm × 20 µm, slice thickness of 500 µm, acquired in 4 min and 16 sec with 20 averages using a gradient-echo sequence. Echo (TE) and repetition times were set to 2.8 ms and 100 ms.

Conclusion

Micro-saddle coil structures with diameters down to 600 µm can be fabricated using an inkjet printing technique based on PDMS and Kapton film substrates. The flexible and high-resolution deposition allows fast and accurate formation of coil patterns. Adapting the sintering treatment improved the adhesion between printed seed layer and substrates, allowing to directly electroplate the pattern towards thicker metal tracks. This approach helps adapting inkjet printing to high-frequency electromagnetic application designs. The concept was successfully demonstrated by acquiring an MR image using a rolled up coil based on a Kapton film. Efforts towards improving the Q-factor of the detector are currently underway, and further characterization including spectroscopy measurements will be reported at a later occasion.

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