

SAFE VISUALISATION AND LOCALISATION OF MR-CATHETERS FOR MR-GUIDED INTRAVASCULAR INTERVENTIONS USING AN OPTICALLY DETUNABLE RESONANT MARKER IN MICRO SYSTEM TECHNOLOGY

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Abstract—An active catheter tracking system has been developed in micro system technology (MST) for the patient-safe localisation of a catheter in intravascular interventions using Magnetic Resonance Imaging (MRI). Two pairs of micro coils, each in Helmholtz configuration, have been fabricated on a polyimide film including the connections to an optically adjustable MOS-capacitance, which was developed especially for this system. With this device, the circuits can be tuned by the power of a laser source, which is synchronized to the MR imaging system. Thus, an automatic detection of this signal in the MR system is possible. The resonance circuits are located at the tip of the catheter. Due to the optical control of the tracking system, there is no risk of resonant RF heating.

Keywords— NMR (MRT); catheter; localisation; tracking system; intravascular intervention

I. INTRODUCTION

Minimal invasive interventions are done more and more using a real-time Magnetic Resonance Imaging System (MR-Imaging). In the clinical practice x-ray fluoroscopy is used for the localisation of the necessary catheter, which is harmful for the patient. For the catheter tracking in a MR-Tomograph (MRT) a fast localisation of the catheter and

the automatic adjustment of the imaging slice is highly desirable. In the past a wide range of techniques have been proposed for these purposes, which are usually classified into active and passive techniques. Active techniques install for example an electrical coil at the tip of the catheter, whose signal is led to the MRT by a coaxial wire [1,2], or use a DC current in an electrical circuit, which is incorporated in the catheter [3]. These so-called active catheter tracking systems have been approved in animal experiments, but they are not applicable for patients, because they hold a big safety risk as the electromagnetic excitation field of the MRT induces high voltages in the elongated conductors in the catheter, which cause a heating of the catheter and thus burnings inside the body [4-7].

Passive techniques visualize the catheter either by paramagnetic materials included in the device, which cause local signal voids [8-10], or by contrast agents increasing the MR signal [11,12]. While passive techniques do not generate any safety hazards, they frequently generate only poor contrast and, more importantly, they do not provide co-ordinates as required for automatic scan plane positioning.

This work focuses on a third group of hybrid

techniques based on standalone parallel resonant circuits, which enhance the MR signal locally [13,14]. These hybrid techniques use electrically active components, however, their signal is received passively by conventional receive coils. Since the localised circuits do not contain elongated conductors, heating due to extended dipole resonances as with the active techniques cannot occur. Moreover, they produce intense local signal enhancements, which, in contrast to the passive techniques, can be controlled externally, e.g. by employing an optically variable impedance. In the context of the project LOMKAT an electrical isolated resonant circuit, realised in micro system technology (MST), with an optically variable capacitor is installed at a tip of the catheter and thus forms such an electrically active component.

II. THEORY

The signal enhancement of resonant markers in MR images originates from two effects: a flip angle amplification during spin excitation and a local signal amplification during signal acquisition. For a resonant circuit comprising an inductance L , a capacitance C and a series resistance R , during RF transmission the B_1 -field of the transmit coil couples an external flux Φ_1 into the inductance of the marker. The resonant circuit reacts with a current producing a total flux Φ_t through the inductor. Thus the inductor adds a flux $\Phi_2 = -iQ\Phi_1$ to the original flux Φ_1 , which results in an additional excitation field $B_2(r)$ giving rise to a locally dependent flip angle amplification with the quality factor $Q = (\omega_{res} L) / R$:

$$\Phi_t = \Phi_1 (1 - iQ) = \Phi_1 - iQ\Phi_1$$

During signal reception, the reciprocal effect takes place. Now local transverse magnetisation represents a local transmitter and couples some flux to the inductor. The resonantly enhanced flux causes an additional transmitted field, which is detected by the receive coil. It is important, that both effects depend linearly on the quality factor Q . Hence, all components of the circuit were designed for high Q for a good signal-to-noise ratio i.e. for a high contrast in the MR image. Numerous detailed simulations of different coils designs have been done for that reason.

III. BASIC CONCEPT

Two of such described stand alone resonant circuits each made out of one pair of micro coils in Helmholtz configuration have been fabricated on a polyimide film including the necessary interconnects to an MOS-

capacitor. These films have been installed at the tip of a catheter thus that the coils are arranged orthogonal in pairs, so that independently from their orientation to the outer magnetic excitation field the signal is maximum.

MOS-capacitors have been developed and fabricated especially for this application. Their capacitance and thus the resonant circuits, by which the signal of the MRT will be modulated, can be tuned by illumination e.g. with a laser source. The triggering will be controlled by the MR-Imaging system and is synchronised with the measurement protocol. That way it is possible to localise the catheter tip automatically. The light is guided in an optical fibre, which is placed inside the catheter (Fig. 1). Due to the optical control of the tracking system and the fact, that the resonant circuit is isolated, there is no risk of resonant RF heating.

IV. LOCALISING THE CATHETER TIP

For the real-time localisation after each excitation two one-dimensional projections of each direction will be made. One projection with the resonant circuit in resonance and one detuned. The triggering will be controlled by the MR-Imaging system and synchronised with the measurement protocol (Fig. 1). With these projections it is possible to calculate the coordinates of the tip and adjust the imaging slice automatically in the MR image. The calculation can be done in the space of 50ms, thus a real-time automatic scan plane positioning and imaging can be done.

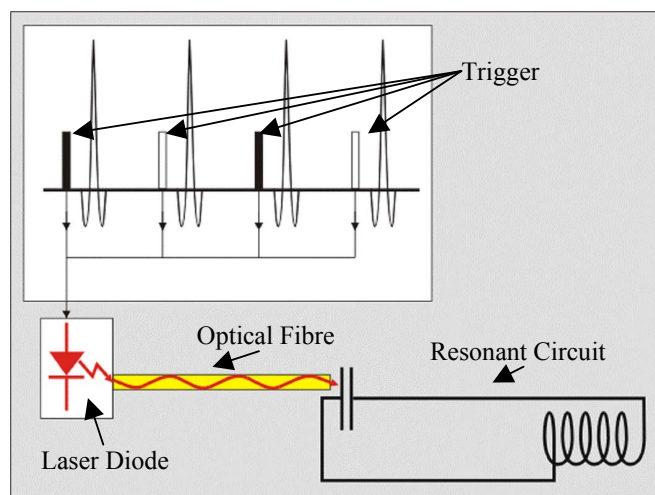


Figure 1: Automatically triggering of the resonant circuit by the MR-Imaging tool.

V. COMPONENTS OF THE RESONANT CIRCUIT

As described the resonant circuits consist of a pair of micro coils fabricated in micro system technology and a

optically tuneable capacitor, which was developed especially for this purpose.

A. Optically tuneable MOS-Capacitor

An essential component of the system is the optical tuneable MOS-capacitor. The layer structure of the capacitor is shown in Figure 2. It bases on a highly doped silicon substrate with a metallic back contact. On the substrate a thin epitaxial silicon layer is deposited with a very thin silicondioxide layer on top, which acts as a dielectric layer. The transparent top electrode on the silicondioxide is made of polysilicon with a metallisation in the form of a grid. The thickness of the silicon-oxide layer and the area of the capacitor define the values of the capacitors.

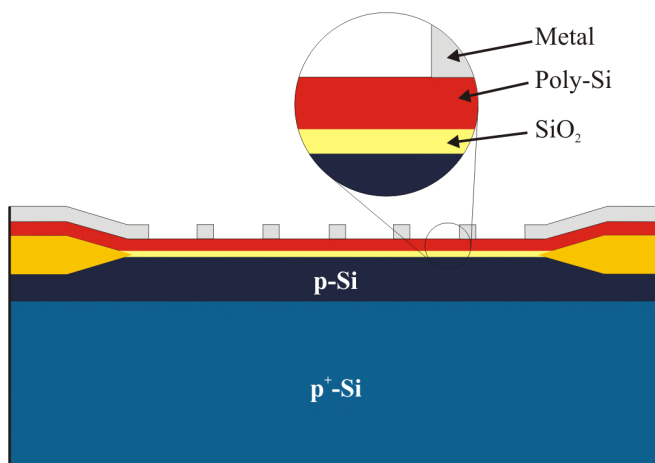


Figure 2: Layer structure of the capacitor. The upper metallisation is structured in the form of a grid.

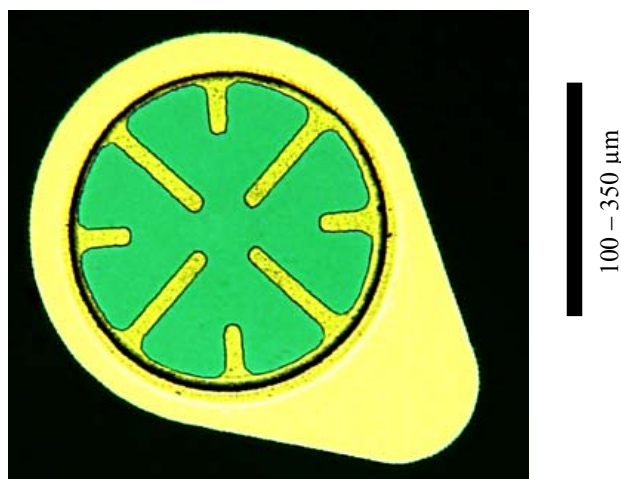


Figure 3: Microscope Image of the MOS-Capacitor.

By illumination the capacitor electron-hole-pairs will be generated inside the epitaxial silicon, which increases the capacitance. The range of variation depends on the laser power light as is shown in figure 4. Capacitance variations

of nearly 400% can be achieved for a laser power of 10mW. For the detuning of the resonant circuit only a small variation of the capacitance is necessary, therefore after exact adjustment of the optical fibre in the special catheter-tips the used laser power can be reduced to 2-3 mW, which can be handled safely.

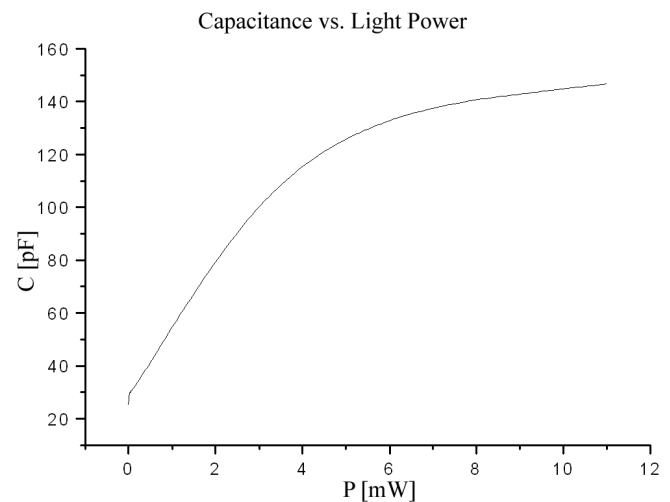


Figure 4: Variation of the Capacitance vs. laser Power

Capacitors of four different diameters were fabricated varying between 100μm and 350μm and capacitances between 5pF and 20pF for the minimal and 19pF to 140pF for the maximum value. The capacitors show a high quality factor of about 40, which is enough for a good signal-to-noise ratio and contrast in the MR-Image. By thinning the substrate the quality factor can be increased furthermore.

B. Micro Coils and Contacts

Due to the very small allowed dimension of the system it is necessary to produce the coils and interconnects using micro system technology, which also offers the advantage of low production costs as they can be produced in a batch process.

The coils with the interconnects to the capacitor are fabricated on a planar polyimide film, because micro system technologies are based on planar substrates. The coils are made by copper electroplating on a titanium-gold layer. The coils and the capacitor are electrically connected by vias through the polyimide film and a patterned backside metal layer, on which the MOS-capacitors are mounted and bonded.

Subsequently the planar system is installed on the catheter-tip, in which the optical fibre is integrated. With these special catheter-tips the MOS-capacitors and the optical fibres are adjusted automatically. Figure 5 shows

the principle diagram and Figure 6 an image of one pair of coils with a connected MOS-capacitor planar and mounted on a catheter. Figure 7 shows a photo of such a pair of coils on a tip in an experimental arrangement.

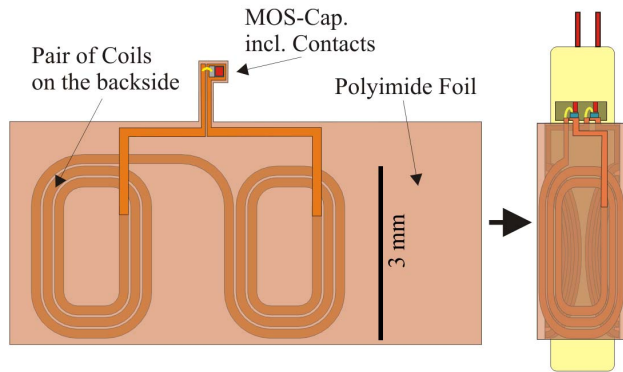


Figure 5: Principle diagram of one pair of coils with a connected MOS-capacitor planar and mounted on a catheter tip.

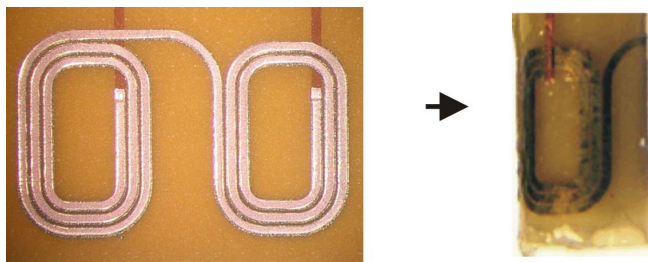


Figure 6: Images of one pair of coils planar and mounted on a catheter tip.

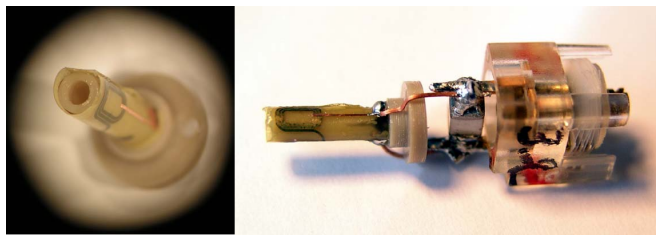


Figure 7: Photos of such a pair of coils on a tip in an experimental arrangement.

The fabricated coils with different dimensions and loops have inductances between 64nH and 194nH with quality factors between 30 and 40. So the complete resonant circuit will exhibit a quality factor of at least 30. This is enough for a good signal-to-noise ratio and thus a fast and reliable localisation of the tip in the MR-Imaging system.

VI. RESULTS

Experiments in a 1.5 T MRT have shown that the pairs

of coils in Helmholtz configuration generate a very high contrast in the MR imaging system. Figure 8 shows a MR image of four coils with different numbers of loops - all coils can be localised very clearly. The resonant circuit was adjusted to the MRT resonant frequency by a discrete and a manually tuneable capacitor (Fig. 7 right).

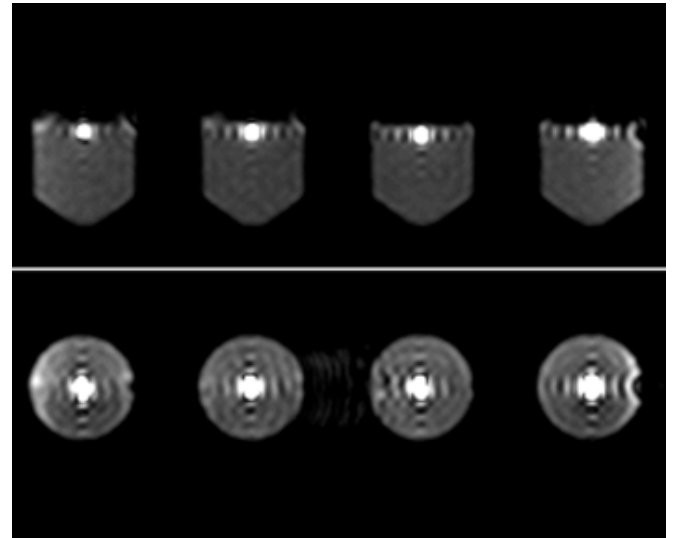


Figure 8: MR-Image of four different coils.

With the components available now, the resonant circuit is presently assembled. The principle of the localisation of such an optically tuneable resonant circuit has been shown in former experiments, however, in which a prototype of the resonant circuit using thin copper wire and a photodiode could be localised very fast in the MRT (Fig. 9). These experiments also showed that a heating in the periphery of the circuit is avoided [15].

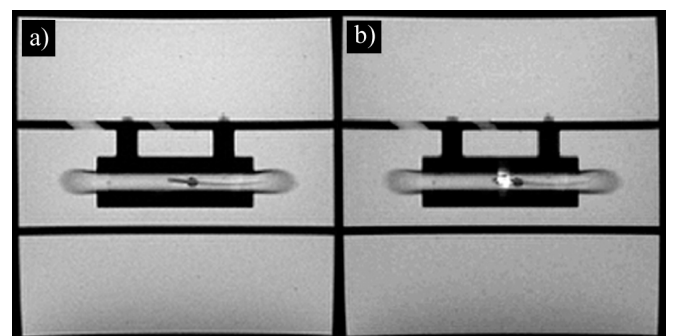


Figure 9: MR-experiment with a prototype of an optically tuneable resonant circuit
a) detuned circuit, b) tuned circuit.

VII. CONCLUSION AND OUTLOOK

It has been shown that both components of the resonant circuit system could be fabricated in micro system technology. The new technique to produce the circuits on a

polyimide film in the plane and to assemble it on a catheter tip afterwards is very useful. The discrete components have high quality factors, so that a fast and reliable localisation is expected. With a prototype it was possible to demonstrate the principle of location in a MR-Imaging tool and that heating due to the resonant circuit is absent. Most of the assembly and packing methods necessary for such a system have been demonstrated, too.

All components of the resonant circuit can be fabricated in batch processes, so that such a special catheter tip is very cost-effective. Furthermore the catheter by it self with the optical fibres can be used more than one time. Due to the system design most of the catheter volume is kept free for addition purposes for the intervention, since e.g. the diameter of optical fibres is small (125µm).

The next steps will be the assembly of the resonant circuits with the new components. In further experiments in the MRT different prototypes and packing methods will be investigated. Subsequently animal experiments will be performed.

So in the future minimal invasive interventions in a Magnetic Resonance Tomograph will be gentler to patients, faster and more cost-effective.

VIII. ACKNOWLEDGEMENTS

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