CATHETER LOCALISATION FOR MR-GUIDED INTERVENTIONS USING A MICRO OPTICALLY DETUNABLE RESONANT CIRCUIT

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Abstract: In the clinical practice x-ray fluoroscopy is used as image guiding modality for intravascular interventions, but this modality is harmful for the patient due to the exposure doses. Therefore and due to the high soft tissue contrast the use of real-time Magnetic Resonance Imaging is increasingly in the focus of interest. For intravascular interventions a reliable and highly contrasted visualisation of the catheter is an indispensable prerequisite, which is only possible in a MR tomograph with a fast localisation of the catheter and an automatic adjustment of the imaging slice. For this purpose two electrical isolated resonance circuits, which are built up in micro system technology, are installed at a special tip of a catheter. These resonance circuits allow a fast localisation of the catheter tip due to the local enhancement of the MR signal. They are composed of two pairs of micro coils fabricated on a polyimide film including interconnects to an optically variable MOS-capacitor, which was developed for this system. With this special device the resonance circuits can be tuned by illumination synchronized with the MR tomograph (MRT), therefore an automatic detection in real-time is possible. Due to the optical control of the tracking system there is no risk of resonant RF-heating.

Introduction

The use of a real-time Magnetic Resonance Imaging System (MRI-System) as image modality for minimal invasive interventions holds a lot of advantages. Among the excellent image contrast of the soft tissue and the possibility of real-time imaging, there is no use of ionising radiation compared with the use of x-ray fluoroscopy. But exactly the x-ray fluoroscopy must be used for the localisation of the necessary catheter, because a normal catheter without any technical modifications are nearly not visible in MR images due to the poor contrast to the surrounding tissue.

For catheter tracking in the MRT a fast localisation of the catheter and the automatic adjustment of the imaging slice is highly desirable, because MR tomography is a slice imaging modality. 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 use locally sensitive receive coils for localisation [1,2] or for visualisation [3,4], for example. Another technique visualises the catheter by means of field inhomogeneities produced by a DC current in a current loop [5]. These so-called active catheter tracking systems have been approved in experiments, but they are not applicable for patients, because they hold a big safety risk: the electromagnetic excitation field of the MRT induces high voltages in the elongated conductors in the catheter, which causes heating of the catheter and thus burnings inside the body [6,7].

Passive techniques visualise the catheter either by paramagnetic materials included in the device, which cause local signal voids [8,9], or by contrast agents increasing the MR signal [10]. While passive techniques do not generate any safety hazards, they generate only poor contrast and, 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 [11,12]. 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 by employing an optically variable impedance. In the context of this project (LOMKAT - BMBF) 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 [13–16].

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 consisting of an inductance L, a capacitance C and a series resistance R, during RF transmission the $\vec{B}_1$ field of the transmitter 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:

$$\Phi_t = \Phi_1(1 - iQ) = \Phi_1 - iQ\Phi_1 \tag{1}$$

Thus the inductor adds a flux $\Phi_2 = -iQ\Phi_1$ to the origi-

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nal flux Φ_1, which results in an additional excitation field $\vec{B}_2(\vec{r})$ giving rise to a locally dependent flip angle amplification (Q is the quality factor of the circuit).

During signal reception, the reciprocal effect takes place. Now the 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, respectively for a good signal-to-noise ratio and with this for a high contrast in the MR image. Numerous detailed simulations of different coils designs have been done for that reason.

Materials and Methods

On a special catheter-tip two of such described standalone resonant circuits have been installed. Each is made out of one pair of micro coils in Helmholtz configuration, which has been fabricated on a polyimide film including the necessary interconnects to an MOS-capacitor. On each capacitor a small capillary is glued in which the optical fibre can easily be integrated and adjusted to the capacitor. Both circuits are fabricated on one polyimide substrate, so that each pair of coils is automatically adjusted orthogonal to the other pair after assembly around the catheter-tip. So independently from their orientation to the outer magnetic excitation field an optimal signal can be observed.

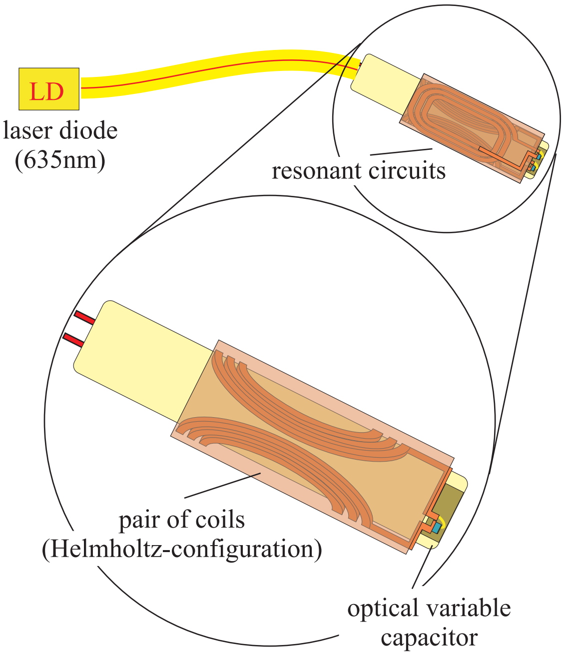

Figure 1: Schematic of the MR catheter with a magnification of the catheter-tip on which one of the optical tunable resonance circuits are installed.

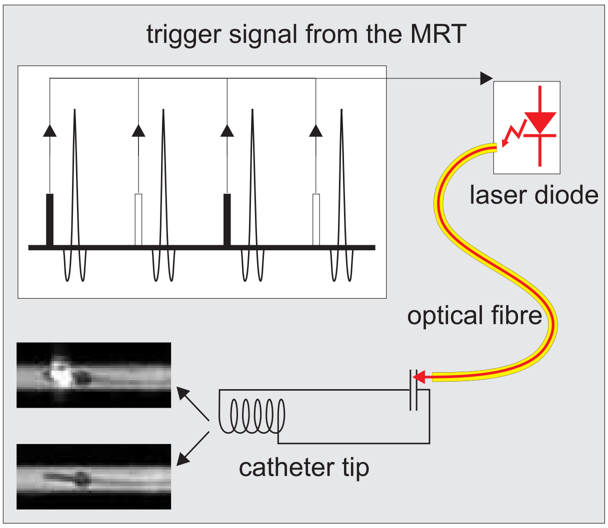

Figure 2: Automatically triggering of the resonant circuit by the MR imaging tool and MR images of the catheter-tip tuned and detuned to the excitation frequency.

Due to the high requirements on the capacitors innovative MOS-capacitors have been developed and fabricated especially for this application. Their capacitance and thus the resonant frequency of the circuits, by which the signal of the MRT will be modulated, can be tuned only by illumination e.g. by a laser source. 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 electrically isolated, there is no risk of resonant RF heating.

The automatic localisation of the catheter-tip and slice adjustment is illustrated in figure 2. By using two one-dimensional projections of each direction a real-time localisation after each excitation can be realised. One projection with the resonant circuit in resonance and one detuned. The triggering of the laser diodes for illuminating the capacitors is controlled by the MR imaging system and is synchronised with the measurement protocol. Therefore two laser diodes connected by an optical fibre to the capacitors can be triggered simultaneously by the MRT. That way it is possible to localise the catheter tip automatically, so that the catheter is always visible on the screen with a high contrast. With the projections it is possible to calculate the coordinates of the tip and adjust the imaging slice automatically. This calculations can be done in the space of 50ms, thus a real-time automatic scan plane positioning and imaging can be done.

As described the resonant circuits consist of a pair of micro coils fabricated in micro system technology and a optically tunable capacitor, which was developed especially for this purpose. The following paragraphs dwell on these two devices.

Optically tunable MOS-Capacitor: The first essential component of the system is the optical tunable capacitor, whose structure bases on a common MOS-capacitor with adapted dopings and a transparent upper electrode (fig. 3). By using a dedicated doping, it is possible to achieve the changing of the capacitance by illuminating the epitaxial silicon (p–Si) under the silicon dioxide (SiO_2) without any bias voltage.

The optical tuning is only possible with a transparent upper electrode, which is formed out of a gold layer in form of a grid and a high conductive transparent zinc oxide (ZnO) layer. The thickness of the silicon dioxide layer and the area of the capacitor define the value of the capacitor.

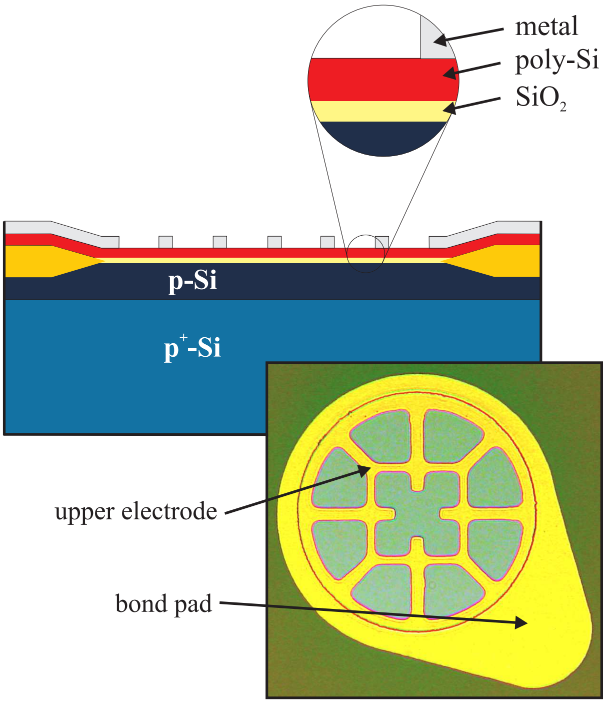

Figure 3: *left:* Layer structure of the capacitor basing on a common MOS-capacitor. The upper metallisation is structured in form of a grid. *right:* Microscope image of the MOS-capacitor with the opened upper electrode.

By illuminating the capacitor electron-hole-pairs will be generated inside the epitaxial silicon (p–Si), 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 by the cappiliaries the used laser power can be reduced to 2-3mW, which can be handled very safely.

Capacitors of fourteen different diameters and geometries were fabricated with capacitance variations between 22pF and 54pF for the minimal and 137pF to 330pF for the maximum value. The capacitors show high quality factors of about 100 at a frequency of 64MHz, which is enough for a good signal-to-noise ratio and with this a high contrasted MR image. By illumination the quality factor decreases indeed, so that the capacitors should be used with small illumination, which enhances also the safety of the system. Furthermore the velocity of the switching is extremely high in the range of micro seconds, so a real-time localisation and with this visualisation is possible.

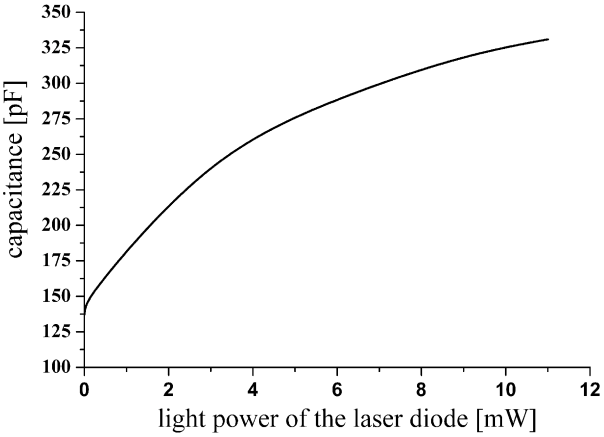

Figure 4: Characteristic of one example of the optically variable MOS-capacitor. Clearly a wide variation of the capacitance by illumination can be observed especially up to 3mW light power of the laser diode.

Micro Coils and Contacts: Clinical studies have shown, that the maximum inflexible length of a 5 French catheter is about 5mm. Due to this very small allowed dimension of the system it is necessary to produce the coils and interconnects using micro system technology, which also offers the advantages of low production costs as they can be produced in batch processes and high reproducibility.

All coils with the interconnects to the capacitors are fabricated on one planar polyimide film, because micro system technologies are based on planar substrates. The coils are made by copper electroplating on a titanium-gold layer by using an advanced thick resist lithography process. They have a length of 3mm and a electroplated height of about 50μm (cp. fig. 5). The two coils and the capacitor of each circuit are electrically connected by vias through the polyimide film and a patterned backside metal layer, on which the MOS-capacitor is mounted and bonded. On the MOS-capacitor a small capillary is glued with an index matched glue, so that an optical fibre can be implemented and adjusted after rolling up the foil. Subsequently the system is installed on a catheter-tip, in which the optical fibre is integrated. Figure 5 shows the principle diagram of one pair of coils with a connected MOS-capacitor planar and mounted on a catheter and photos of such a pair of coils planar and on a tip in an experimental arrangement.

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

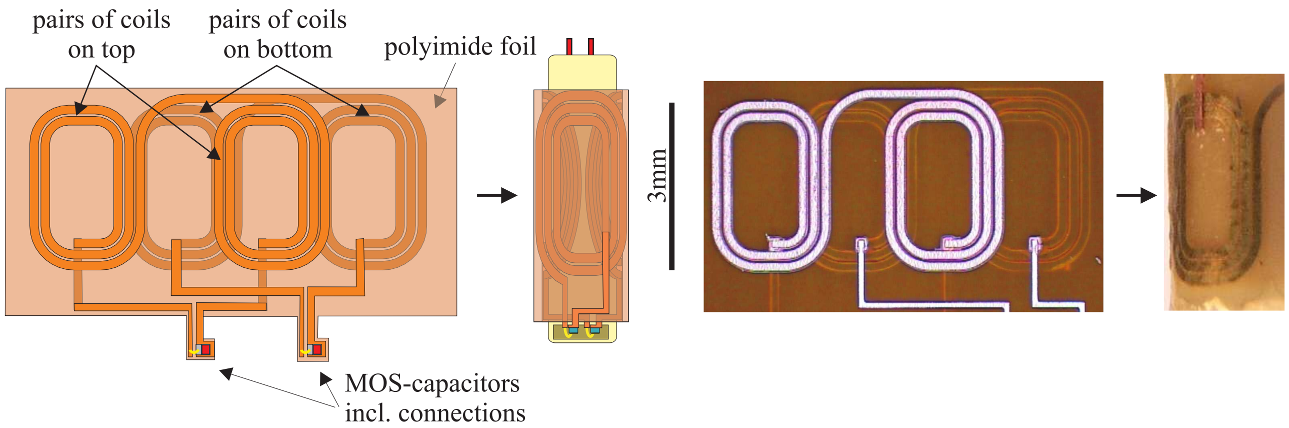

Figure 5: *left:* Principle diagram of both systems on one foil - each with one pair of coils and a connected MOS-capacitor planar and mounted on a catheter tip. After wrapped around the tip the two pair of coils are automatically adjusted orthogonal to each other, so that there is always an optimal signal independently of the direction of the system to the outer magnetic excitation field. *right:* Images of the coils planar and mounted on a catheter tip.

Results

A prototype of the optical variable resonance circuit was built up and characterised in a 1,5T magnetic resonance tomograph. In figure 6 (left side) two states of the resonance circuit (tuned and detuned to the excitation frequency) are shown, what was achieved only by varying the illumination. Clearly a high contrast can be observed, so that a fast (real-time) and reliable localisation is possible. These experiments also showed that a heating in the periphery of the circuit is avoided [16].

Due to the small dimensions of the circuit, the accuracy of the localisation is very high, so that these marker can also be used for motion measurements inside the body.

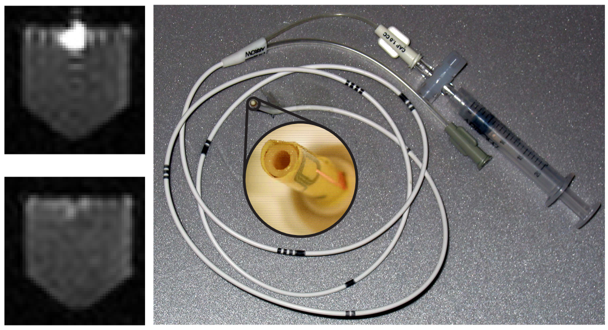

Figure 6: MR images of the optical detuned and tuned state of the resonance circuit and image of a prototype of the MR catheter with special catheter-tip.

Discussion and Conclusion

It has been shown that both components of the resonance 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 localisation 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 itself 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 complete integration of the resonant circuits to a clinical catheter. 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.

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