Novel optically tunable capacitor for RF safe tuning and decoupling of intravascular MR coils

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Objective: The motivation for the application of intravascular imaging coils is to gain high SNR images from a local area. To maximize SNR, proper tuning and matching of such coils is of utmost importance [1]. Moreover, active decoupling during transmit is important for image quality and RF safety of intravascular coils. In current interventional devices, tuning and matching is usually accomplished with fixed elements, which is a limitation, because the load and the shape of interventional coils may change as with expandable coils. Photodiodes have been used for optical decoupling of such coils [2,3], but this concept requires additional capacitors in series and parallel to the photodiode, which requires additional connections and complicates the tip assembly. Furthermore, the photodiode concept is not appropriate for tuning. Remote tuning and matching with varactors [4] or PIN diode based decoupling is problematic in interventional devices, because the required control leads are prone to RF heating. Recently, a transformer-based transmission line for the MR signal has been proposed that can vastly reduce RF heating of active interventional devices [5]. However, this transmission line does not transmit DC as required for varactor based tuning and PIN diode based decoupling. Here, we propose an optically tunable capacitor based on a dedicated metal-oxide-semiconductor interface for these purposes.

Materials and Methods: A basic metal-oxide-semiconductor capacitor (MOS-C) is a three layer structure with a semiconductor base, an insulating oxide layer, and a metal layer [6]. The device has a capacitance, which can be varied as a result of changes in the charge distribution in the semiconductor. Usually, this is achieved by applying a voltage to the device. Alternatively, the same effect can be achieved by illuminating the interface between the semiconductor and the oxide layer.

A customized MOS-C device with a modified layer structure was designed for tuning and decoupling of intravascular coils. A highly doped silicon substrate was used to achieve minimal series losses in the outer connection. A lowly doped epitaxial silicon layer was applied on top, followed by a silicon oxide layer. Instead of a plain metal electrode, first, a polycrystalline silicon electrode was applied that is transparent in the visible and infrared (λ= 650-900 nm). At last, a structured metal electrode with windows for illumination was applied for connection with a bond wire (Fig.1). With appropriate choices for the active area of the device, the thickness of the insulation layer, the doping levels of the semiconductor layers and the thickness of the active epitaxial layer, the overall capacitance as well as the capacitance range due to illumination was adjusted. MOS-C devices with three different sizes of the active area (approx. 0.03mm², 0.06mm², 0.09mm²) were produced. The largest lateral dimension of the devices is 500µm, their thickness is only 100µm.

The complex impedance of the devices was measured with an impedance analyzer at 64MHz as a function of illumination. Therefore, the light of a laser diode (660nm, maximal output 35mW, Hitachi) was coupled to the device via an optical fiber, that was glued onto the device. One of the devices was applied to tune and decouple a prototype expandable intravascular MR receive coil. The coil was constructed from thin insulated copper wire that was glued to a polyurethane tube (2mm diameter) forming a single 55mm long and 2mm wide loop. Within the loop section, the tube was cut along its long axis such that the coil could be expanded from a closed state to an open state by shortening the corresponding tube section. A MOS-C device with a capacity of 24pF without illumination and an appropriate fixed capacitor were connected in parallel to the coil. The fixed capacitance was chosen such that the circuit was tuned to 63.87MHz with a fully opened wire loop and without illumination of the MOS-C. The MOS-C was fitted via the optical fiber to the laser diode as for the impedance measurement. The tube with the intravascular coil was placed in a dish filled with phantom liquid. MR images were acquired with a cartesian FFE sequence (TR 3ms, TE 1.5ms, flip angle 10°) using a circular surface coil (200mm diameter), while the intravascular coil was manually expanded in steps from a closed to a fully expanded state. For each state, two images were acquired, one with a fixed laser power of 3.24mW and one with a power adapted to optimally tune the intravascular coil to the Larmor frequency at 1.5T.

Results and Discussion: The impedance measurements at 64MHz showed capacities of 8pF, 16pF, and 24pF for the three differently sized devices without illumination which is exactly proportional to the size of the active areas. Quality factors of 50 to 80 were measured at 64MHz without illumination. This range is sufficient for the application in intravascular coils, since it matches the range of quality factors achieved with loaded intravascular coils themselves. With only 2mW light power applied at the 24pF device, a remarkable increase of the capacity by 100% was achieved (Fig.2). A maximal capacitance of 77pF corresponding to a 220% increase was measured for an illumination with 16mW.

The MR images in the upper row of Fig.3 show the intravascular coil with a fixed illumination of 3.24mW, which corresponds to a capacitance increase of 29pF. This is sufficient to decouple the coil, so that the interior of the loop does not contribute any signal. Only spins very near at the coil wire still contribute some signal. In the lower row, the coil has been tuned to resonance by simply adjusting the laser power. Consequently, the signal level and SNR within the loop is strongly increased.

Conclusion: A very compact optically tunable capacitor based on a dedicated metal-oxide-semiconductor interface has been developed. The device was successfully applied to tuning and decoupling of an expandable intravascular MR receive coil. In the future, such a device may be used to allow RF safe remote optical tuning and matching and decoupling of miniature receive coils for intravascular imaging and catheter tracking.

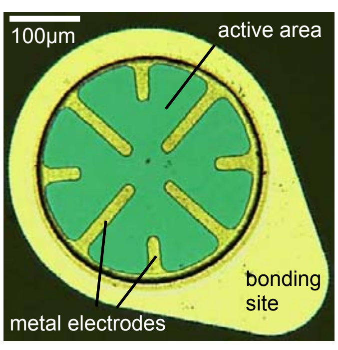

Fig.1

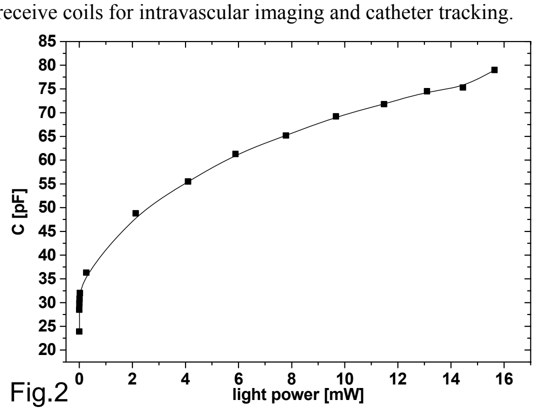

Fig.2

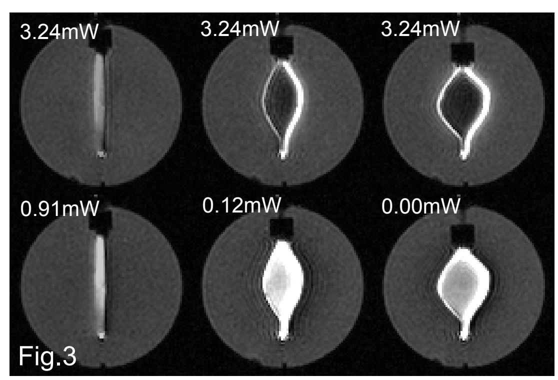

Fig.3

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