# Harmonic excitation of MR signal for interventional MRI

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**Target audience**: MR physicists, RF engineers, interventional radiologists.

**Purpose**: MR-detectable devices are important for interventional procedures, and should provide a clear imaging signature while not degrading diagnostic imaging quality. Here, a new MR-detectable probe design is presented, based on excitation of MR signals by high-frequency RF harmonics generated by the probe with a non-linear element.

**Methods**: An implantable probe was designed to excite MR signals when driven by an external RF filed at half-resonance frequency. The design and principle of operation of a second harmonic generating microcoil (SHMC) are shown in Fig. 1. The SHMC was constructed using two inductive parallel loops with diameters of 4 mm, connected by a 15 pF non-magnetic capacitor, as shown in Fig. 1A. A low barrier (<250 mV) and low capacity (< 0.3 pF), Schottky diode (HSMS-2852, Avago Technologies) was inserted in the middle point of one of the loops. In the absence of RF excitation, the diode is open and the circuit is tuned at a resonance frequency of 200 MHz. During the 200 MHz RF pulse, the diode is transiently closed by the direct voltage in the circuit, and the resonance frequency is shifted to 400 MHz, as shown in Fig. 1B. A single-turn loop 200 MHz transmit coil was constructed with an LC trap filter blocking the 400 MHz frequency. All studies were performed on a Bruker 9.4T Biospec system (proton resonance frequency of 400 MHz) using the experimental setup for harmonic excitation MRI shown in Fig. 2. A standard multislice spin-echo imaging with TE/TR=6/1000 ms and 3D FLASH imaging with TE/TR=1.1/50 ms and flip angle of 10 degrees, was initially performed. 3D SHMC FLASH images were acquired using square 500 μs RF pulses at 200 MHz and an RF power level of 35 dBm applied to the transmit coil. MR harmonic imaging experiments were performed with an agarose phantom and with an experimental animal model with implanted SHMC. All animal experiments were performed in accordance with the Guidelines for Animal Experimentation of the Johns Hopkins School of Medicine.

**Results**: A T2 MR image of a 3% agarose phantom prepared in a standard 10 mm NMR tube with the embedded SHMC (Fig. 1A) is shown in Fig. 3, top left. Magnetic susceptibility artifacts from the capacitor and the diode are visible in the image. A matching slice from the 3D gradient echo SHMC image is shown in Fig. 3, bottom. Only sample areas next to the SHMC contributed to the detected MR signal. A 3D reconstruction of fused gradient echo images obtained using a standard RF coil and the SHMC excitation are shown in Fig. 3 right. *In vivo* MR experiments were performed after implanting SHMC in the mouse back and positioning animal in a 30 mm RF resonator, with the transmit RF coil attached to the animal (Fig. 4A). Coronal and axial fused images obtained with a standard FLASH (gray-scale) and SHMC-generated harmonics (colored image) are shown in Fig. 4 B,C. Coronal images were generated by maximum intensity projections of 6-8 slices extracted from 3D data matrices for the FLASH and SHMC imaging, respectively.


**Fig. 1**. Circuit diagram of SHMC.

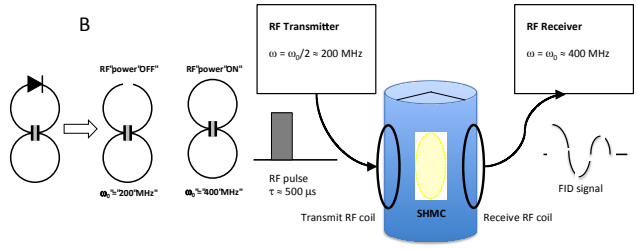


**Fig. 2**. Design of the SH excitation experiment on a 9.4T MR scanner.

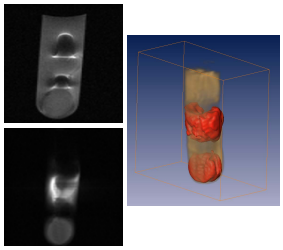

**Fig. 3**. Standard and SHMC images of the phantom with embedded coil.

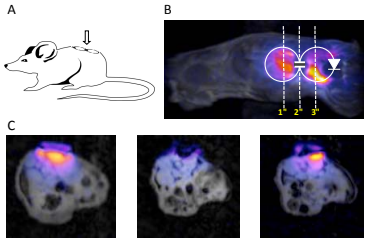


**Fig. 4**. *In vivo* second harmonic excitation MR experiment.

**Discussion**: We demonstrated robust generation of second harmonic RF signals by a dedicated RF circuit containing a nonlinear RF element (a fast switching low-barrier Schottky diode). Harmonic excitation was used to produce MR signals in phantom and animal models using implanted SHMC. To our knowledge, this is the first demonstration of the use of this technology for MRI. The SHMC circuit becomes active only when an RF field on half-resonance frequency is applied, and, therefore, produces minimal interference with standard MRI. As the nonactivated SHMC is tuned to half-resonance frequency, $\omega_0/2$, and there are no connecting leads, minimal heat generation is expected during standard MR acquisition, which facilitates real-time acquisition to guide interventional procedures.

**Conclusion**: We have developed and demonstrated a novel technique for selective excitation of MR signals by a second harmonic generating device. The method can be used to track the probe position overlaid with anatomical images during interventional MRI. The main advantage of the design is lack of lead wires and minimal heating of the probe during standard MR experiments.