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AN ACTIVE TRANSMIT/RECEIVE NMR MAGNETOMETER FOR FIELD MONITORING IN ULTRA HIGH FIELD MRI SCANNERS

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Abstract: *We present a miniaturized active nuclear magnetic resonance (NMR) magnetometer consisting of a susceptibility matched field probe and a PCB based RF transceiver. Thanks to its transmit-receive (TX/RX) capabilities, the system can be used to monitor the spatio-temporal field evolution during a magnetic resonance imaging (MRI) scan and thereby allows for a correction of gradient field imperfections to improve image quality. The magnetometer can be tuned for magnetic fields ranging from 7 T to 15.5 T and achieves a resolution of 14.8 nT measured in a 9.4 T whole body scanner.*

Keywords: *NMR magnetometry, ultra high field MRI, gradient field monitoring, active NMR field probes*

Introduction

MRI is one of the most powerful imaging techniques in modern medicine because it provides excellent soft tissue contrast without exposing patients to potentially harmful ionizing radiation. Here, ultra high field MRI scanners with their associated higher signal-to-noise ratios have the potential to provide improved spatial resolutions but any magnetic field imperfections (e.g. due to hardware limitations, drifts or patient movement) deteriorate the image quality. NMR field probes which record these imperfections can therefore be used to perform an appropriate predistortion of the gradient waveforms [1] or a software-based postcorrection of the MR data [2]. Receive-only field probes make use of the scanners TX coil to excite the spin ensemble which limits their applicability for the real-time monitoring of MR experiments [3]. Passive probes are prone to crosstalk because they transmit small RF signals via long cables.

To overcome these limitations, in this paper, we present an active NMR magnetometer consisting of a field probe and a miniaturized RF transceiver. The RF transceiver both generates the RF pulse exciting the spin system and performs a low-noise amplification and downconversion of the MR signal induced in the TX/RX coil. The system therefore provides the possibility of a localized NMR measurement with robust signal levels at its output which can be directly digitized. The operating frequency ν_0 can be programmed from 300 MHz to 660 MHz corresponding to a magnetic field between 7 T and 15.5 T. In this paper, we demonstrate the operation in an ultra high field MRI whole body system (Magnetom 9.4 T, Siemens Healthcare, Erlangen, Germany).

Methods

The active NMR magnetometer consists of a field probe and an RF transceiver PCB as shown in Fig. 1. The design of the field probe is based on [3]. A glass capillary with an inner diameter of 800 µm containing H_2O as NMR sample is surrounded by a 6 turn solenoid coil. Since the coil is used for excitation as well as detection, the effective sample volume is limited to 1 µL which results in a high spatial resolution. The sample is surrounded by a susceptibility-matched ellipsoidal casing to maintain a homogeneous magnetic field inside the probe and connected to the PCB using a shielded cable of approximately 2 cm length to minimize susceptibility artifacts induced by the packages on the PCB.

The field probe is tuned to the resonance frequency of $\nu_0 = \gamma/(2\pi)B_0 = 399.72$ MHz and matched to 50 Ω using two non-magnetic trimmer capacitors according to Fig. 1. This tuning/matching network is followed by an RF switch (HMC284, Hittite Microwave, Chelmsford, MA, USA) to alter between TX and RX mode. The frequency synthesizer (TRF3765, Texas Instruments, Dallas, TX, USA) generates the frequency ν_{LO} from an externally supplied reference signal $\nu_{ref} = 500$ kHz. During TX, the excitation pulse with the frequency $\nu_{LO} \approx \nu_0$ is boosted by a power amplifier (PA) (PHA1+, Mini-Circuits, Brooklyn, NY, USA). The RX front end consists of a low-noise am-

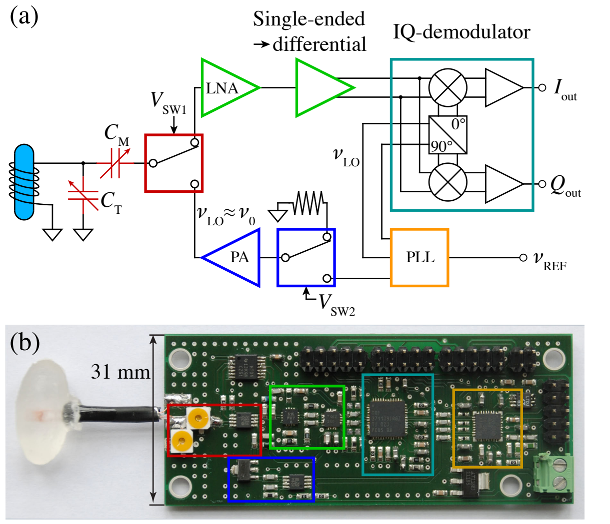

Figure 1: (a) Block diagram of RF transceiver architecture and (b) photograph of PCB with the attached field probe.

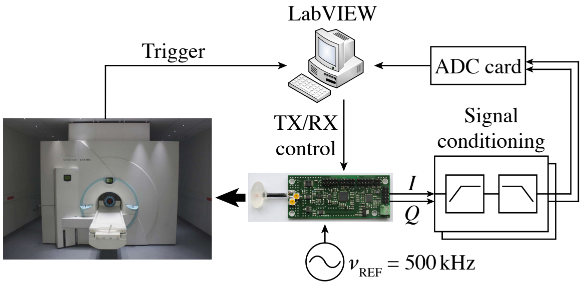

Figure 2: Illustration of the experimental setup.

plifier (LNA) (HMC616, Hittite) followed by a differential amplifier (ADL5565, Analog Devices, Cambridge, MA, USA) generating a balanced input for the demodulator. The receiver (TRF371109, Texas Instruments) performs a quadrature homodyne demodulation of the signal to minimize the receiver noise figure and allow for a distinction between positive and negative frequency offsets which is crucial for the magnetometry application. The receiver also incorporates a programmable gain amplifier, which can be used to tune the overall RX gain between 31 dB and 55 dB. The setup to perform MR experiments on the Siemens 9.4 T Magnetom system is shown in Fig. 2. Analog-to-digital conversion (ADC) was performed by a data acquisition card (NI PCIe-6363, National Instruments, Austin, TX, USA), the data processing and control of the switch signals was realized in LabVIEW (National Instruments). An external trigger signal from the scanner control unit can be used to synchronize the gradient waveforms with the magnetometer. The receiver and ADC bandwidths (≥ 1 MHz) are sufficiently large to deal both with strong gradient strength and modern arbitrarily shaped gradient pulse waveforms.

Results

The H_2O sample is excited close to resonance with 90° flip angle pulses with $\tau_{90°} = 23.75\,\mu s$ at the PA output power level of 16 dBm. The unfiltered time-domain free induction decay (FID) is shown in Fig. 3 (a) and the real part of the FFT is shown in Fig 3 (b). For the FFT, a time-domain matched filter with $\tau = T_2^*$ was applied to maximize the frequency-domain SNR. The measured full width at half maximum (FWHM) linewidth in this condition is 21 Hz.
A series of 101 experiments with no applied field gradients and a repetition time $T_R \gg T_1$ was performed to evaluate the achievable frequency resolution. Figure 3 (c) shows the deviation of the resonance frequency $\hat{\nu}_0$ from the average value $< \hat{\nu}_0 >$. Defining the frequency resolution as $R_{\hat{\nu}_0} = 3\sigma$, the measured frequency resolution is 0.63 Hz, corresponding to a magnetic field resolution of 14.8 nT.

Discussion

We presented an NMR magnetometer for measuring gradient field imperfections in MRI scanners. Because a miniaturized transceiver is directly attached to the field probe, no external excitation field is required allowing for a measurement of the local magnetic field strength during MR scans.

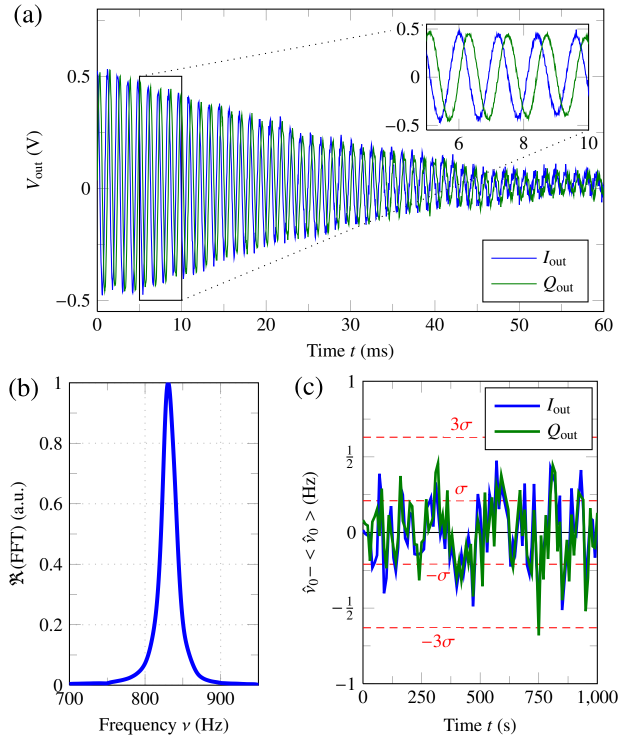

Figure 3: (a) Unfiltered time-domain signal of the field probe containing H_2O (inset: close-up view of the IQ signals; T_{ACQ} = 4 s, F_S = 0.5 MHz; measured T_2^* = 29 ms) and (b) real part of the FFT. (c) Resonance frequency spread $\Delta\hat{\nu}_0 = \hat{\nu}_0 - < \hat{\nu}_0 >$ in a series of 101 measurements (T_R = 10 s, T_{ACQ} = 4 s).

Future work is directed towards a further reduction of the PCBs form factor (use of smaller components, test pin removal) and finally the implementation of the transceiver as a CMOS chip. Furthermore, by changing the NMR active nuclei from protons to i.e. fluorine, RF interferences from MR experiments on the field probe could be eliminated. The ultimate goal of the work is to realize an array of field probes monitoring the magnetic field evolution during MRI scans to compensate for spatial- and time-varying magnetic field imperfections.

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