COSI Transmit: Open Source Soft- and Hardware Transmission System for traditional and rotating MR

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Synopsis

As part of the open source imaging initiative (www.opensourceimaging.org), a collaborative effort to build an open source MRI, we proposed and built a transmission/reception RF system mostly consisting of open source components for traditional and rotating spatial encoding schemes. COSI Transmit is based on a GNU Radio compatible software defined radio (SDR) as a spectrometer, a 1kW RF-power amplifier, T/R switch, low noise preamplifier and a transmit/receive solenoid RF coil. The system operates in the frequency range from 1.8-30MHz (B0=0.042-0.7T) and can potentially be extended to B0=1.27T. Material cost of the system is ~3000€.

Purpose

MRI is a crucial medical device that is beyond the reach of many patients throughout the world[1]. Cost effective open source imaging (COSI) is part of the open source imaging initiative (OSI²) currently building an affordable open source MRI system in order to address this issue[2]. Here we present COSI transmit, an open source transmission/reception system for low field (B_0=0.042-0.7T) MRI of traditional and rotating spatial encoding schemes[3]. COSI transmit consists of a spectrometer, RF power amplifier (RFPA), transmit/receive switch, low noise preamplifier and RF coil.

Methods

A schematic of COSI transmit modules is displayed in Fig.1a.

The primary requirement for the spectrometer hardware was GNU Radio[4] and gr-MRI[5] compatibility. This approach allows hardware independent developments of imaging techniques. An USRP1[6] SDR (f=DC-6GHz, ADC: 12bit 64MS/s, DAC: 14bit 128MS/s) was implemented with two transmit[7] and one receive[8] daughterboard (f=0-30MHz). We extended the gr-MRI[5] code utilizing GPIO pins embedded in the board allowing the use of a single SDR for stepper motor control of rotating gradient fields used for spatial encoding[9,10].

A RF amplifier (P_{out}=1kW peak, f=1.8-54MHz) was developed consisting of a driver stage, an output stage, a low pass filter, a blanking/unblanking circuit and a cooling circuit (Fig.2a). For the driver a two stage linear amplifier[11] (gain:33-34dB, P_{out}=5W, f=1.8-150MHz) and for the output stage the design of W6PQL[12], a 1kW peak solid state pallet amplifier (gain:22-27dB, f=1.8-54MHz) based on a power LDMOS transistor (BLF188XR) was chosen. A 1.5kW low pass filter[12] at the output suppresses unwanted harmonics. A level converter is used at the SDR output to match the TTL high for RFPA unblanking. For un-/blanking the amplifier, the power supply voltage is switched on/off respectively via CMOS transistors. In addition after 3µs the LDMOS source is clamped to discharge the capacities and suppress any additional RF noise of the output stage during MR signal reception.

A passive T/R-switch[13] (3-5MHz, 47dB isolation, P_{max}=1.3kW) was used to connect the RF coil and the RFPA. For MR signal pre-amplification a low noise preamplifier[14] is utilized (f=150kHz-30MHz, gain:18-20dB, noise figure=1-2dB).

The RF coil was constructed based on electromagnetic field simulations[15] for a frequency of f=3.63MHz, which is the center frequency of our prototype Halbach magnet. A solenoid design was chosen as a transmit/receive RF coil to adapt to the Halbach magnet B_0 field distribution. RF coil loading was modeled by a spherical sample with 70mm diameter representing muscular tissue. The length and number of turns was adjusted to reach a homogenous B_1^+ field distribution inside the sample (Fig.5c).

The simulations were validated with S_{12}-measurements[16] of a pickup loop positioned along a straight line at one end of the RF coil. B_1 calibration of the pickup loop was done in a known B-field of a TEM-cell[17] (Fig.5a,b,d). This approach allows for a low cost validation of the EM fields at such low frequencies without using more expensive E- or H-field sensors.

Results

The spectrometer is capable of producing arbitrary shaped RF-pulses, un-/blanking the RFPA, recording acquired data and controlling rotating gradient fields (Fig.1c). Pulse length, amplitude, readout-length and –delay can be chosen freely.

The RFPA successfully amplified rect- and sinc-pulses generated by the spectrometer (Fig.3b,d). A signal amplitude of 500mV at the input leads to an output voltage level of 200V which corresponds to a total gain factor of 52dB and a power level of 800W in a 50Ω system (Fig.3). The expected distortions observed (Fig. 3) will be addressed by digital predistortion techniques. The RFPA shows good linearity for the investigated frequency range f=1.8-54MHz (B_0=0.042-1.27T) with a maximum power output of around 1kW peak power (Fig.4).

The RF coil consists of N=20 windings, length=200mm and radius=48mm (Fig.5d). The measured Q-factors are Q_{loaded}=155 and $Q_{unloaded}$=189. Simulated B_1^+ amplitude in the RF coil center is ~2694μT/√kW with a B_1^+-field inhomogeneity within the sample <3.4% (Fig. 5c). The mean difference between validation measurements and simulations was -5.1±4.2% for absolute and 1.2±4.5% for relative values. The whole system occupies a volume of around (50x30x35)cm³. The total cost of the system is ~3000€ (SDR:1000€; RFPA:1500€; T/R-Switch:370€; LNA:20€; RF-coil:100€).

Conclusion

An affordable (~3000€) MR transmission/reception system was developed by using mainly open source hardware components. In its current configuration COSI transmit can be used for B_0=0.042-0.7T (extendable to 1.27T) MRI systems with traditional and rotational spatial encoding schemes. Technical documentation of the system will be made available at www.opensourceimaging.org according to the principles of open source hardware. Further work will focus on developing a fully open source spectrometer, T/R switch and RFPA module allowing to improve the performance and lowering costs.

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References

[1] World Health Organization, "Global Health Obervatory (GHO) data: Medical equipment (density per million population)", 2014

[2] Winter L, et. al., ISMRM, 2016, #3638

[3] Cooley CZ, et al., MRM, 2015;73(2):872-83

[4] GNU Radio, http://gnuradio.org/

[5] Hasselwander C.J., et al., JMR, 2016;270:47:55

[6] USRP1, Ettus Research, Mountain View, USA

[7] LFTX daughterboard (0-30MHz), Ettus Research, Mountain View, USA

[8] LFRX daughterboard (0-30MHz), Ettus Research, Mountain View, USA

[9] Winter L, et al. ISMRM, 2015, #3568

[10] Blümler P, Conc Magn Reson Part B: Magn Reson Eng, vol. 46, pp. 41-48, 2016.

[11] Funkamateur, Bausatz für QRP-Linear-Endstufe, DL2EWN, http://www.box73.de/

[12] W6PQL, http://www.w6pql.com/1kwsspafor18-54mhz.htm

[13] NMR Service GmbH, Erfurt, Germany

[14] LNA4HF, 9A4QV, http://lna4hf.blogspot.de/

[15] CST MWS 2012, Darmstadt, Germany

[16] Spectrum analyzer, Rohde & Schwarz, München, Germany

[17] Klepsch T., et al., BMT, 2012; 57(1)

Figures

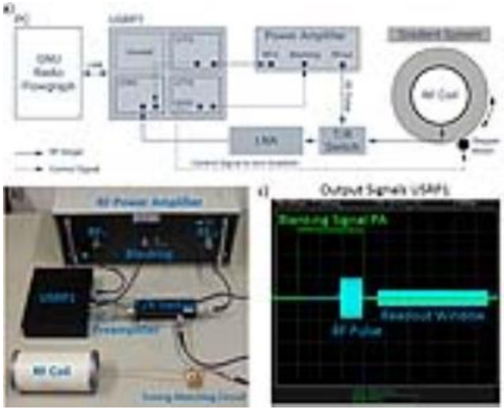

Figure 1 – Schematic (a) and photograph (b) of COSI transmit: GNU Radio flowgraph runs on a computer, controls and communicates with USRP1 via USB. The LFTX daughterboards generate the RF-pulse, blanking signal and readout window (c). Data acquisition is synchronized to the transmission by feeding back the readout window signal to the LFRX receive-board. The RFPA amplifies the RF-pulse, which is send to the TX/RX-RF coil via T/R-switch. The received signal is amplified with an LNA and digitized on the LFRX-board. GPIO pins on the LFTX-board are used to control a stepper motor driving circuit for gradient system rotation.

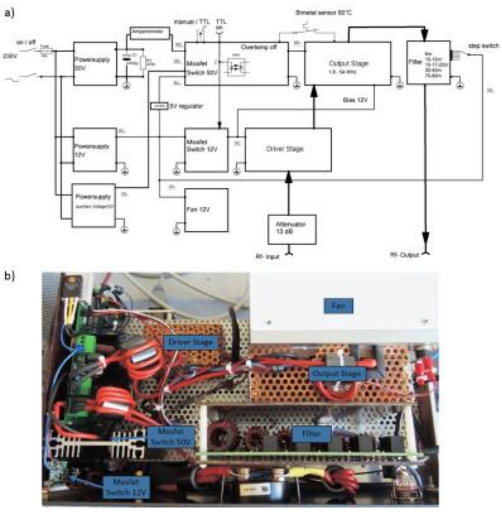

Figure 2 – Schematic (a) and photograph (b) of the RF-power-amplifier: The RFPA consist of a driver stage (Gain=33-34 dB) and an output stage (Gain=22-27dB, P_{out}=1kW). The adjustable low pass filter at the output suppresses unwanted harmonics. To blank/unblank the amplifier, the 12V and 50V power supplies are connected and disconnected to the ampflification stages respectively using CMOS transistors.

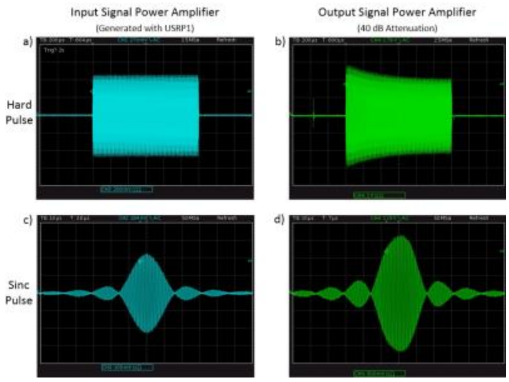

Figure 3 – 1200 µs long rect pulse with an amplitude of 500mV (a) and a 120µs long sinc pulse with a maximum amplitude of 200mV (c) are shown on the left side. Both pulses are generated by the SDR spectrometer. On the right side (b,d) the same pulses are shown after amplification with the RF-power amplifier and 40dB attenuation. The expected distortions observed will be addressed by digital predistortion techniques.

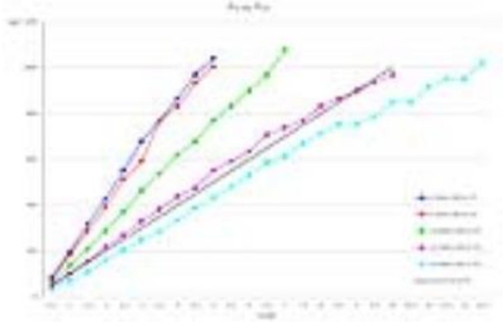

Figure 4 – Input power P_{in} plot versus the output power P_{out} of the RFPA for the Lamor frequencies of hydrogen at magnetic field strengths B_0= 0.1T, 0.2T, 0.3T, 0.5T and 1.0T showing good linearity over the investigated frequency range.

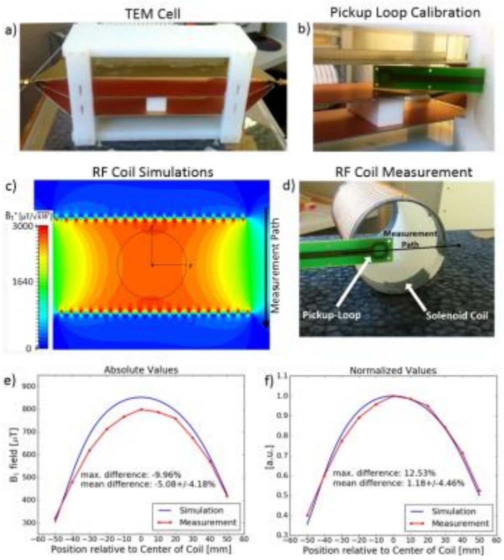

Figure 5 – B_1^+ measurement setup of the solenoid RF coil and comparison to the EMF simulations. a) TEM cell with known B field distribution b) Pickup loop calibration with the spectrum analyzer. c) Simulated B_1^+ field distribution of the solenoid coil and measurement path position. d) Pickup loop measurements along a straight line at the end of the RF coil. e) Absolute and f) normalized comparison of simulated and measurement B_1^+ values of the RF coil.