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Development and Implementation of the Analog Electronics for a 20 MHz Pulsed NMR Spectrometer

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Abstract

Low-field nuclear magnetic resonance (NMR) systems offer a cost-effective alternative to high-field devices for medical point-of-care applications but result in lower resolution. This makes it more important to care for precise excitation and high-resolution amplifiers to detect weaker signals. This project addresses the development of the analog hardware of a portable 20 MHz pulsed NMR spectrometer for hemoglobin analysis. Components for the proton spin excitation and receiving chain were chosen, including high-resolution low-noise amplifiers. A duplexer and probe were modified, frequency tuning and impedance matching were performed and the overall system was tested. The excitation chain successfully delivered sufficient energy to excite protons, and weak signals in the µV range could be amplified. However, tests have not shown a free induction decay yet. The results highlight key limitations of the current setup and demonstrate the need for improved excitation–receiving separation and enhanced amplification, providing a foundation for further optimization.

I. Introduction

Nuclear magnetic resonance (NMR) spectroscopy is a well-established diagnostic procedure for studying molecular structures and interactions based on the magnetic properties of atomic nuclei [1].When exposed to an external magnetic field B_0 the nuclei align themselves to this field. The injection of radio-frequency (RF) pulses excites the nuclei and leads them to resonate at the Larmor frequency, which is proportional to the magnetic field strength [2]. The subsequent release of energy produces free induction decay (FID) signals, which are processed with Fourier transform to produce characteristic spectra used for diagnostic purposes [1]. High-field NMR systems provide excellent resolution but are expensive, require intensive maintenance, and rely on liquid helium cooling due to high current flowing through the coils. As a cost-effective alternative for medical point-of-care applications, compact tabletop NMR devices using permanent magnets in the low-frequency range (10 MHz to 100 MHz) have gained attention [3]. The aim of this project is to develop a low-cost, portable 20 MHz NMR spectroscope for point-of-care hemoglobin analysis. This paper focuses on the design of the analog hardware (Figure 1) consisting of two sections: one for exciting the protons by feeding energy into the probe and another for forwarding and amplifying the received FID signal for detection and further processing.

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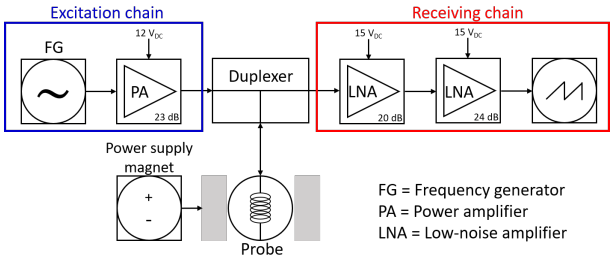

Figure 1: Block diagram of the overall setup of the 20 MHz NMR spectrometer containing the excitation chain (blue), duplexer, probe, electromagnet with power supply and the receiving chain (red).

II. Methods and materials

The following section explains the function of the components in the NMR spectroscope, and describes the experiments performed for system testing.

II.I. Excitation chain

The excitation chain consists of a frequency generator (SDG2082X, Siglent Technologies, Augsburg, Germany) for generating the excitation pulses and a power amplifier that amplifies the power injected into the system. With a gain of 23 dB, a frequency range from 1.8 MHz to 52 MHz and a quiescent current of 200 mA, a suitable 5 W linear amplifier (BX-034, Funkamateur, Berlin, Germany) was selected. It is supplied with a voltage of 12 V_{DC}.

II.II. Receiving chain

The receiving chain consists of two amplifier stages, which are designed to amplify the FID signal emitted by the protons to an extent that it can be displayed on the oscilloscope (WaveSurfer 24MXs-B, Teledyne GmbH – LeCroy, Heidelberg, Germany). A signal at the level

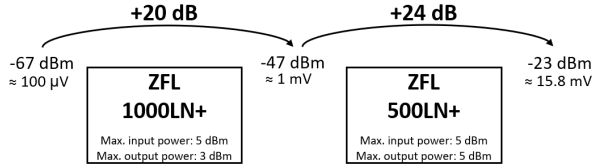

Figure 2: Visualization of the theoretical signal gain calculation of the low-noise amplifier chain for an assumed signal amplitude of 100 µV.

of µV is expected [2]. In order to detect such weak signals, the amplifiers must have the lowest possible noise figure. Two low-noise amplifiers ZFL-1000LN+ and ZFL-500LN+ (Mini-Circuits, New York, USA) were selected due to to their gains of 20 dB and 24 dB, frequency ranges of 0.1 MHz to 1000 MHz and 0.1 MHz to 500 MHz, and a noise figure of 2.9 dB. Both run on 15 V_{DC} and have a maximum input RF power of +5 dBm. Figure 2 shows the theoretical calculation of the total gain of these amplifiers for an assumed signal amplitude of 100 µV. Based on this, a FID of 100 µV should give an output signal of 15.8 mV in the oscilloscope.

II.III. Duplexer and probe

Two central components connect the excitation chain to the receiving chain: the duplexer and the probe. The purpose of the duplexer is to feed the excitation signal into the probe and to transfer the received signal from the probe to the low-noise amplifier chain. An isolator at the input of the duplexer prevents the current from flowing backwards. It consists of four 1N4148 diodes and a 10 kΩ resistor to ensure that power losses are minimized. At the output of the duplexer a clipper, consisting of two 1N4148 diodes, protects the low-noise amplifiers from overvoltage. The key component is a π-filter which works as a quarter-wave filter [4]. The probe is a LC resonant circuit consisting of a coil (length $l = 7.8 \times 10^{-3}$ m, diameter $d = 5.88 \times 10^{-3}$ m, number of windings $N = 17$) and a capacitor connected in parallel. Both the duplexer and the probe are based on the design by Louis-Joseph and Lesot [4] and were adapted to this NMR system in a previous work. Both components had to be modified to ensure proper functioning. To optimize the energy absorption in the sample, the components must be precisely tuned and their impedance matched to the resonance frequency. Therefore, the π -filter in the duplexer circuit was modified. The two original capacitors were replaced by three capacitors connected in parallel, each with a trimmable capacitance in the range of 8 pF to 50 pF. These can be set to the optimum value during frequency tuning. In the probe a trimmable capacitance of 8 pF to 50 pF was connected in parallel to the existing capacitor. Another trimmable capacitance was connected in series to this parallel circuit to allow precise frequency tuning and impedance matching.

II.IV. Tuning and matching

The frequency tuning and impedance matching to 50 Ω of the duplexer and the probe were carried out using a

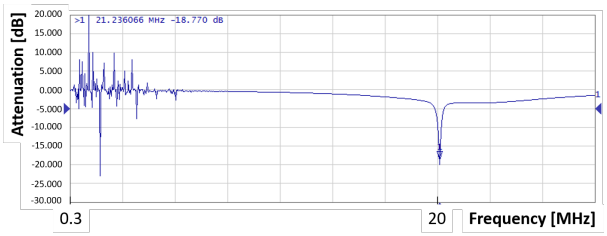

Figure 3: Input reflection coefficient S11 of the resonant circuit with a narrow peak at a frequency of 21.23 MHz. The y-axis shows the attenuation from 20 dB to −30 dB.

network analyzer (E5071C, Keysight Technologies, Santa

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Rosa, USA). The input reflection coefficient (S11) was determined. S11 describes the part of the input signal that is reflected back to the input due to incorrect impedance matching. As can be seen in Figure 3, the input reflection coefficient reaches a minimum of approximately −18 dB at a resonance frequency of 21.23 MHz. The peak is particularly narrow at this frequency. The determined system impedance of the resonant circuit is 45.7 Ω.

II.V. Validation and testing

After frequency tuning and impedance matching, the system was tested extensively. All tests are described in the following sections.

II.V.1. Excitation chain

To test the functionality of the excitation chain, pulses with a length of 5 µs and a frequency of 21.23 MHz were fed into the probe from the frequency generator via the power amplifier and duplexer. The pulses were detected via a measuring coil ($l = 1.5 \times 10^{-3}$ m, $d = 3.6 \times 10^{-3}$ m, $N = 2$) located in the probe, which was directly connected to the oscilloscope. The amplitude was increased stepwise from 500 mV_{pp} to 3 V_{pp}.

II.V.2. Receiving chain

To test the receiving chain, the frequency generator was used to simulate the FID signal. Pulses with a length of 5 µs and a frequency of 21.23 MHz were directly injected into the amplifier chain to evaluate the signal-to-noise ratio (SNR). The amplitude was gradually increased from 1 mV_{pp} to 3 mV_{pp}. The amplified signal was measured using the oscilloscope, which was directly connected to the second amplifier stage. In a further experiment, a continuous sine wave with a frequency of 21.23 MHz was coupled into the amplifier chain. A voltage divider was inserted between the frequency generator and the first amplifier stage. It was intended to reduce the voltage to the predicted signal level. The amplitude was reduced in several steps from 1.15 mV_{pp} to 22 μV_{pp} and the signal was measured after the amplifier chain using an oscilloscope.

II.V.3. Overall setup

To test the complete setup, the system was assembled as shown in Figure 1. Using the frequency generator, a 2.5 µs excitation pulse with a frequency of 21.23 MHz and an amplitude of 3 V_{pp} was generated in channel 1 and fed into the system. A 2.5 µs long pulse with a frequency of 21.23 MHz and an amplitude of 1 V_{pp} was injected into the probe via a measuring coil on channel 2 to simulate the FID signal. The delay of this simulated signal was increased step by step from 1 µs to 150 µs to determine the acquisition delay of the system.

III. Results and discussion

The results of the performed tests are described and discussed in the sections below.

III.I. Excitation chain

Testing the excitation chain shows that at a voltage of 3 V_{pp} at the frequency generator, a pulse with a voltage of 11 V_{pp} is measured in the probe as shown in Figure 4.

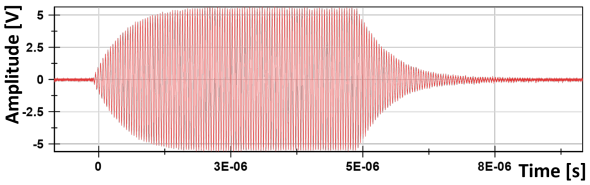

Figure 4: Excitation pulse, measured in the probe with a measuring coil ($l = 1.5 \times 10^{-3}$ m, $d = 3.6 \times 10^{-3}$ m, $N = 2$).

Since the measuring coil only has two windings while the coil in the probe has 17, the measured voltage must be multiplied by a factor of 8.5 to maintain the actual voltage in the coil. The voltage fed into the probe is therefore approximately 11 $V_{pp} \times 8.5 = 93.5\,V_{pp}$. A pulse with this amplitude should provide sufficient energy to excite the protons in the inserted sample [5]. At the same time, the waveform of the pulse is a clear sine wave, which indicates efficient energy transfer.

III.II. Receiving chain

Tests of the receiving chain show that a sine wave of approximately 115 μV_{pp} can be recognized as sinusoidal signal with an amplitude of 40 mV_{pp} and thus displayed. The measured gain values differ from the values specified in the data sheets with 23 dB (ZFL-1000LN+) and 28 dB (ZFL-500LN+). Since the exact size of the FID signal is unknown it may not be possible to display the signal due to insufficient SNR. An additional amplifier stage is required to ensure that the signal can be sufficiently amplified and displayed. Further amplification is also necessary regarding future signal acquisition using a Field Programmable Gate Array (FPGA), as this requires 2 V_{pp} at the input.

III.III. Overall setup

Testing the overall setup revealed that no signal could be detected with this configuration. The tests showed that the two anti-parallel diodes on the duplexer that are designed to protect the low-noise amplifiers from overvoltage are not sufficient. The diodes limit the voltage from the excitation pulse, but they still have a forward voltage of about 1 V which leads the amplifier chain into saturation. This means that the amplified voltage no

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longer follows a clear sine wave and the signal is strongly distorted. A signal can be seen at the earliest 33 µs after excitation and the recovery time of the amplifier is 150 µs as can be seen in Figure 5. One reason that no

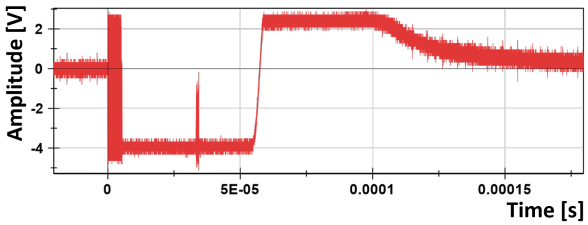

Figure 5: Behavior of the amplifier chain after the excitation pulse. A signal can be seen 33 µs after excitation. The recovery time of the amplifier is about 150 µs.

signal was found could be insufficient homogeneity of the magnetic field. If the magnetic field is not homogeneous enough, the FID signal decays much faster than assumed [3]. The decay time is shorter than the recovery time of the amplifier chain, so that the signal cannot be displayed. Further research should aim to reduce the recovery time to a minimum, for example by using a switch that efficiently separates the excitation part from the reception part. Detailed tests with different kinds of switches are scheduled. Another solution could be a new design of the duplexer which consists only of a quarter wave cable that produces an anti-node inside the probe and a node at the output of the duplexer [6]. In addition, future work should focus on homogenizing the magnetic field. If necessary, the magnetic field should be modified by a process known as shimming to minimize inhomogeneities [7].

IV. Conclusion

A complete analog setup of a 20 MHz pulsed NMR spectroscope prototype was implemented. The excitation chain was successfully assembled and tested. A pulse with an amplitude of 93.5 V_{pp} can be fed into the probe to excite the protons inside an inserted sample. The clear sine wave of the pulse indicates efficient energy transfer. The duplexer and probe were modified to enable frequency tuning and impedance matching. They were successfully tuned and the resonance frequency was found at 21.23 MHz. This provides the foundation for transferring enough energy to the probe to excite the protons and thus, receive a FID signal. Nevertheless, it cannot be ruled out that the quality factor of the resonance circuit is insufficient. Further optimization should be considered. A sine wave with an amplitude of approximately 115 μV_{pp} can be amplified to 40 mV_{pp} and recognized as a sinusoidal signal by the receiving chain of the system. However, the SNR needs to be improved by attaching additional amplifier stages. Further amplification is required, particularly with regard to future signal acquisition using a FPGA, which expects an input range of up to 2 V_{pp}. The current overall setup is not yet suitable for reliable signal detection. Saturation of the amplifier chain caused by insufficient suppression of the excitation pulse leads to signal distortion and delays detectable signal acquisition. To overcome this limitation, further experiments should focus on the separation of the excitation and receiving chain. Possible solutions such as fast switching or an optimized duplexer design should be tested. Additionally, future work should provide detailed magnetic field characterization and potential shimming.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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