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Fully differential low noise amplifier for MPI/MPS

A. Malhotra[1,*] · H. Schwegmann[1,2] · J. Schumacher[1] · X. Chen[1] · T.M. Buzug[1]

[1]Institute of Medical Engineering, University of Lübeck, Lübeck, Germany
[2]Institute for Robotics and Cognitive Systems, University of Lübeck, Lübeck, Germany
[*]Corresponding author, email: malhotra@imt.uni-luebeck.de

Abstract

Magnetic particle imaging (MPI) is a novel tomographic imaging modality, which uses static and dynamic magnetic fields to measure the magnetic response generated by superparamagnetic iron oxide nanoparticles (SPIONs). For the characterization of the SPIONs magnetic particle spectroscopy (MPS) is used. In the current research, a low noise amplifier (LNA) suitable for MPI and MPS is presented. LNAs play a significant role in the receive chain of MPI and MPS systems by amplifying the signals from the nanoparticles while keeping the noise induced through its own circuitry minimal. The LNA is based on a fully differential amplifier (FDA) in a summing configuration to reduce noise. The input voltage noise of the prototyped LNA with a receive coil and a 50 Ω resistance in a bandwidth of 200-600 kHz is 300 pV/$\sqrt{\text{Hz}}$ (NF = 14.05) and 1.76 nV/$\sqrt{\text{Hz}}$ (NF = 11.93) respectively.

I Introduction

Magnetic particle imaging (MPI) is an emerging modality providing quantitative information on the distribution of oxide nanoparticles (SPIONs) [1]. Magnetic particle spectroscopy (MPS) is being used for characterizing the SPIONs according to their magnetic properties for usage in MPI. MPI scanners have the capability to provide the quantitative and spatial distribution of these SPIONs in a three-dimensional volume known as field of view (FOV) [2]. For acquiring the characteristic response of the SPIONs, the hardware is divided into transmit chain and receive chain with different passive and active components. Low noise amplifiers (LNA) are present in the receive chain and are responsible for the amplification of the characteristic SPIONs response to the dynamic range of the analog to digital convertor (ADC) in acquisition card. The amplitude of the SPIONs signal can be very low (ranging from a few nV to 100 μV) depending on the hardware, magnetic properties as well as concentration of these nanoparticles [3]. Therefore, the LNA's primary task is to amplify the nanoparticle signal while keeping the noise induced due to its own circuitry at a minimum. Several techniques and configurations are used for manufacturing an LNA, which rely on CMOS, MOSFETS, and Op-amps [4]. In this research the focus is on a fully differential amplifier (FDA) based on the parallelization technique (also known as summing configuration), to reduce the internal noise produced by its own circuitry. An LNA not only amplifies the SPIONs response but also the noise present at the input while adding inherent noise produced by its own passive and active components. With the help of parallelization technique, the input signal (correlated signal) is amplified by a factor N, but the uncorrelated noise increases just by a factor of $\sqrt{N}$, where N is the number of Op-amps in parallel [5]. Theoretically, by increasing the value of N, the inherent noise can be mitigated but the input resistance and capacitance of the Op-amp provides a limiting factor. The input resistance forms a voltage di-

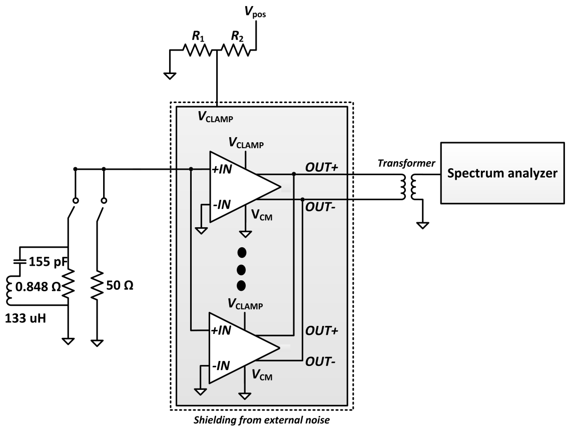

Figure 1: Block diagram of the designed FDA consisting of four LMH6553 in parallel. Resistors R_1 and R_2 are used to set the clamping voltage for the protection circuit. Pin -IN is grounded just to operate it in single-ended input configuration but the FDA is capable of handling fully differential signals.

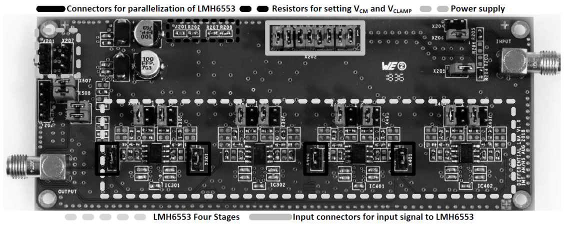

Figure 2: The PCB of the designed FDA consisting of four LMH6553 in parallel. The components in the white box are the four LMH6553 with their components. The jumpers in the black box are for connecting them in parallel.

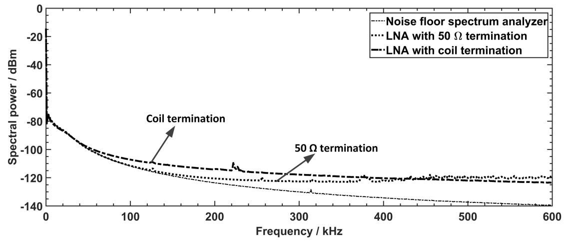

Figure 3: The noise spectrum of the designed FDA based on LMH6553 connected with a receiving coil (marked in blue) with an internal resistance of approximately 0.848 Ω and a self-capacitance of approx. 155 pF and a 50 Ω resistance (marked in red) at a gain of G = 110.60. The curve in black is the noise floor of the spectrum analyzer.

vider and reduces the amplitude of the SPION's response; therefore, to compensate this the internal gain of the Op-amp has to be increased while keeping the GBWP (gain-bandwidth product) in check. On the other hand, the input capacitance determines the resonance peak of the receive chain, having a direct impact on the measurement bandwidth. In the current research, an FDA is used instead of single-ended Op-amp as an FDA provides added noise immunity. The noise immunity results from a higher CMRR (common-mode rejection ratio) due to the differential pathways. Another advantage of an FDA is that it doubles the output signal in comparison to the single-ended Op-amp as the transfer function (V_{Od}) of an FDA is given by

$$V_{Od} = V_{id} \times A(f), \quad \text{where} \, V_{id} = (V_{IN+}) - (V_{IN-}),$$

where V_{id} is the input differential voltage, $A(f)$ is the frequency-dependent gain and V_{IN+} and V_{IN-} are the voltages at the differential input of an FDA. An FDA is also capable of mitigating its own even-order distortions due to symmetry in the feedback loops. In the next section, the hardware design of the LNA is presented.

II Material and methods

The designed LNA is based on an LMH6553 (Texas Instruments, USA). The bandwidth of an LMH6553 is 900 MHz and has an integrated output clamping circuit to provide transient over-voltage protection to the ADC present in the signal chain of an MPI/MPS device. The differential input resistance and capacitance is 15 Ω and 0.5 pF respectively with a CMRR higher than 38 dB [6]. According to the datasheet the input noise voltage and the input current voltage at 100 kHz is 1.2 nV/$\sqrt{\text{Hz}}$ and 13.6 pA/$\sqrt{\text{Hz}}$ with second harmonic distortion (HD2) at -79 dBc [6]. The block diagram, as well as the measurement setup for the noise analysis of the prototyped LNA, is shown in Fig. 1. The LNA consists of four FDAs in parallel; this parallelization can be easily removed with the help of the jumpers present on the PCB board. The LNA is connected to the spectrum analyzer EXA-N9010A (from Keysight, USA) with the help of 1:1 voltage transformer for noise analysis. This is necessary, as the spectrum analyzer is not capable of handling differential inputs.

The designed PCB is shown in Fig. 2. The size of the PCB is 125.47 mm x 25.45 mm consisting of 160 components. The PCB consists of four layers with a separate ground and power plane. The differential signal paths were designed to be as symmetrical as possible to reduce potential balancing errors as well as distortions due to asymmetries.

Table 1: The spectral density in dBm/Hz, input noise and NF of the designed FDA based on an LMH6553 with a gain of G = 110.60 with 50 Ω resistor and a receive coil.

Input	Bandwidth (kHz)	Input noise (nV/$\sqrt{\text{Hz}}$)	Output noise (nV/$\sqrt{\text{Hz}}$)	NF (dB)
50 Ω	200 – 400	1.58	175	10.99
	200 – 600	1.76	195	11.93
Receive coil	200 – 400	0.36	40.19	15.92
	200 – 600	0.30	33.14	14.05

III Results

For testing and calculating the input voltage noise, the measurements are done in two setups, with an input termination of a 50 Ω resistor and in the other case with a receive coil with an internal resistance of approximately 0.551 mΩ and a self-capacitance of approx. 2.5 pF. Fig. 3 shows the spectral noise density obtained with the help of the spectrum analyzer with two different inputs as shown in the block diagram (Fig. 1). From the above data, an in-built function present in the spectrum analyzer for calculating the spectral noise density in dBm/Hz is used. The calculated input noise, output noise and the NF (noise figure) are presented in Table 1.

The input noise parameters of the FDA are quite impressive, especially with the receive coil termination. The input noise of the FDA in the frequency range of 200-600 kHz with the receiving coil at the input is around 299 $\mathrm{pV}/\sqrt{\mathrm{Hz}}$z and with a 50 Ω resistance at the input, the noise is around 1.76 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$. The difference in the input noise between the two measurements can be attributed to the higher resistance of the 50 Ω resistor in comparison to the receive coil.

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Author's Statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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