Ankit Malhotra* and Thorsten Buzug

Op-amp based low noise amplifier for magnetic particle spectroscopy

Abstract: Magnetic particle spectrometry (MPS) is a novel technique used to measure the magnetization response of superparamagnetic iron oxide nanoparticles (SPIONs). Therefore, it is one of the most important tools for the characterization of the SPIONs for imaging modalities such as magnetic particle imaging (MPI) and Magnetic Resonance Imaging (MRI). In MPS, change in the particle magnetization induces a voltage in a dedicated receive coil. The amplitude of the signal can be very low (ranging from a few nV to 100 µV) depending upon the concentration of the nanoparticles. Hence, the received signal needs to be amplified with a low noise amplifier (LNA). LNA's paramount task is to amplify the received signal while keeping the noise induced by its own circuitry minimum. In the current research, we purpose modeling, design, and development of a prototyped LNA for MPS. The designed prototype LNA is based on the parallelization technique of Op-amps. The prototyped LNA consists of 16 Op-amps in parallel and is manufactured on a printed circuit board (PCB), with a size of 110.38 mm x 59.46 mm and 234 components. The input noise of the amplifier is approx. 546 pV/√Hz with a noise figure (NF) of approx. 1.4 dB with a receive coil termination. Furthermore, a comparison between the prototyped LNA and a commercially available amplifier is shown.

Keywords: Magnetic Particle Imaging, Magnetic Particle Spectroscopy, Low Noise Amplifier, Op-amps, Noise analysis.

https://doi.org/10.1515/cdbme-2017-0125

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1 Introduction

Magnetic particle spectrometry (MPS) is an investigative modality which instigated with the initiation of the magnetic particle imaging (MPI). MPI is an emerging modality providing quantitative information on the spatial distribution of the magnetic nanoparticles such as superparamagnetic iron oxide nanoparticles (SPIONs) [1]. Hence, to achieve high sensitivity and sub-millimetre resolution, the SPIONs used in the MPI play a vital role. MPS is a novel measurement system for characterization of these nanoparticles on the basis of the magnetic properties of these particles.

In MPS a sinusoidal signal of a particular frequency is applied to the SPION sample through a transmit coil. Due to the non-linear magnetization of the SPION this leads to an induction of a voltage in the receive coil. This received signal gives information regarding the signal strength, physical properties such as hysteresis as well as insight into the size distribution of SPIONs [2]. A simplified block diagram of a one-dimensional MPS is shown in **Figure 1**. The signal

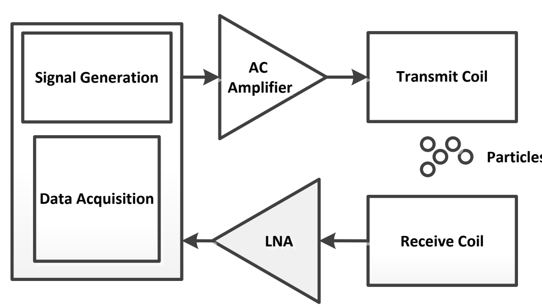

Figure 1: A simplified block diagram of an MPS system.

induced in the receive coil can be in a range lower than 1 µV (- 110 dBm) depending upon the physical properties and concentration of the particles. This is where low noise amplifier (LNA) comes into play. The paramount function of the LNA is to amplify this particular signal to the dynamic range of the data acquisition card without changing the signal integrity and keeping the inherent noise of LNA as low as possible. Therefore, it is important for the LNA to have a good signal to noise ratio (SNR) and noise figure (NF). To demonstrate the noise characteristics of the prototyped LNA, its input noise, output noise, spectral power density and NF are presented.

1.1 Basic principle

There are a number of techniques and configurations for producing LNA which relies on CMOS [3], MOSFETS [4] and Op-amps [5]. This research focuses on LNA based on parallelization technique (also known as summing configuration), to decrease the internal noise produced by its own circuitry. An LNA not only amplifies the input signal but also amplifies the noise in the input signal as well as the inherent noise produced by the various passive and active components present in the LNA itself. By using the parallelization technique, the input signal (correlated signal) is amplified by a factor of N, but the uncorrelated noise (LNA noise) increases just by a factor of $\sqrt{N}$, where N is the number of amplifiers in the summing configuration.

In theory, by increasing the value of N, we can mitigate the inherent noise generated by LNA, but proper designing of the LNA, as well as the selection of the Op-amps used in LNA, plays a significant role. To deduce the merit of the LNA, foremost criteria is noise density. The noise density is specified as voltage noise density in $nV/\sqrt{Hz}$ and the current noise density in $pV/\sqrt{Hz}$. For simplicity, these values are always referred to its input noise density thus making it independent of the gain of LNA. A spectrum analyzer can be used to measure the average noise given in dBm/Hz density from which the output noise of the LNA can be calculated.

The values obtained in dBm/Hz can be easily converted in dBW by 1000 mW = 1W; +30 dBm = 0 dBW; -30 dBm. Hence, the power in dBW is:

$$dBW = Measurement\ (dBm/Hz) - 30$$
$$W = 10^{\frac{dBW}{10}}$$
$$Output\ Noise = \sqrt{Resistance * W}$$

NF signifies the degradation of the signal to noise ratio as it passes through the system. It can be defined by the noise factor (F) which is:

$$F = \frac{S_{In}/N_{In}}{S_{Out}/N_{Out}} = \frac{S_{In}/k_b TB}{S_{In}G/Out} = \frac{N_{Out}}{GTBk_b}$$

Where, N_{out} = noise power output; G = device gain; k_b = Boltzmann's constant; T = temperature in Kelvin; B = bandwidth; F = noise factor. From this formula the NF can be derived by using the equation:

$$NF = 10log_{10}(FGTBk_b) - 10log_{10}(G) - 10log_{10}(TBk_b)$$

In the next part, the theoretical calculations for the output noise, input noise as well as the total output noise is described according to the Op-amp as well as the topology used in the current research.

2 System design

The design consists of the LT6232 (from the Linear Technology), a rail to rail Op-amp with an input noise voltage of 1.1 $nV/\sqrt{Hz}$ and an input noise current of 1 $pA/\sqrt{Hz}$. The advantage of this particular Op-amp is its availability in SSOP (Shrink Small Outline Package) package. Therefore, a total of four Op-amps in a single integrated circuit (IC) are present, which makes the layout easier and efficient. Other specifications include a bandwidth of 215 MHz and an input bias current of 5 µA. The operating supply voltage for the particular design is set to ±5 V. This Op-amp is operated on the non-inverting configuration. The noise calculation for one of the parallel stages with a gain (G) of 101 is explained below. The gain is set with the help of two resistors R_1 = 15 kΩ and R_2 = 150 Ω. The resistor noise (e_r) can be calculated in terms of voltage noise by using

$$\sqrt{4 * k_b * T * R} \approx 0.13\sqrt{R}\ nV/\sqrt{Hz},$$

where k_b is the Boltzmann constant in Joules per Kelvin, T is the resistor's absolute temperature in Kelvin and R is the resistor value in Ohms (Ω).
Using the above formula, the noise produced by R_1 is 15.92 $nV/\sqrt{Hz}$ and by R_2 is 1.59 $nV/\sqrt{Hz}$. But as R_2 is connected to the non-inverting pin of the amplifier, the noise has to be multiplied with the gain of the amplifier. Hence the total noise generated by R_2 is 160.80 $nV/\sqrt{Hz}$. The input current noise (e_i) and input voltage noise (e_v) can be calculated using:

$$e_i = Input\ Current\ Noise\ Density * Eq.\ Circuit\ of\ R_1\ and\ R_2 * G \approx 15\ nV/\sqrt{Hz}$$

$$e_v = Input\ Voltage\ Noise\ Density * G \approx 111.1\ nV/\sqrt{Hz}$$

The total output noise (E_{out}) can be calculated by

$$E_{out} = \sqrt{{e_r}^2 + {e_i}^2 + {e_v}^2} \approx 196.67\ nV/\sqrt{Hz},$$

and the total input noise (E_{in}) is:

$$E_{in} = \frac{E_{out}}{G} \approx 1.94\ nV/\sqrt{Hz}.$$

Therefore, an apt selection of the resistors plays an important role in the noise profile of the prototyped LNA. Moreover, other parameters such as topology of the amplifier and the layout design can lead to the various noise sources in the circuit due to parasitic capacities.

2.1 Measurement setup

The block diagram, as well as the measurement setup of the prototyped LNA, is shown in **Figure 2**.

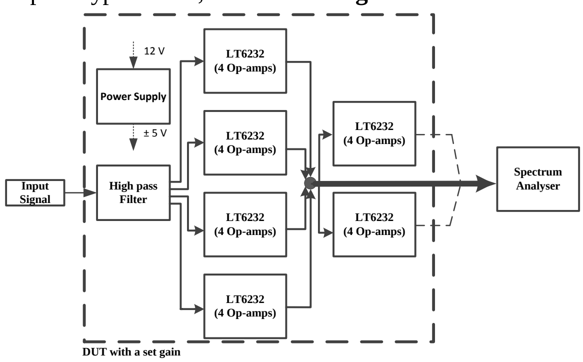

Figure 2: Block diagram of the prototyped LNA and the measurement setup. Here DUT means device under test. For comparison, this is replaced with the commercial LNA.

The LNA is divided into two stages and both stages consist of an LT6232. The first stage has 16 Op-amps and the second stage has 8 Op-amps in parallel. All the Op-amps have a non-inverting configuration. For this particular research, only the first stage is used. The second stage is just added to get some extra gain if required. There are jumpers present on the PCB to use the different stages depending upon the input signal from the coils. The input power supply to the PCB is 5 V DC with 500 mA, 25 W from a power adapter (MPU 31-102 from Dehner Eletronik GmBH). This 5V DC is converted to ± 5V DC with the help of LT8582 (from Linear Technologies) which is a DC/DC converter with fault correction and a switching frequency of 2.5 MHz, which is above the input transmit frequency of 25 kHz, which is generally used in MPS. For the measurement, the LNA is directly connected to the spectrum analyzer EXA-N9010A (from Keysight). 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 approx. 0.551 mΩ and a self-capacitance of approx. 2.5 pF. The gain is also varied for the two setups to see the variance in noise at low and high gains. Therefore, two gains are used, 105 and 500, respectively. The spectral density is measured from 1 kHz to 1 MHz. The RBW (resolution bandwidth) and VBW (video bandwidth) of the spectrum analyzer are set to 1 kHz and 100 Hz, respectively. For each measurement 100 averages are taken and the number of points is 500. By using the in-built function of the spectrum analyser, spectral noise power is calculated at 600 kHz by keeping the BW at 1 Hz. Furthermore, the prototyped LNA is compared with commercially available LNA SR560 (from Stanford Research Systems). The results will be presented in the next section.

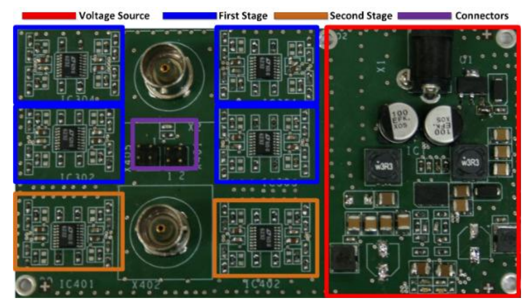

Figure 3: Image of the prototyped LNA with all the modules.

Figure 3 shows the image of the populated PCB without housing. The BNC connectors are used for the input and output signals and all other areas are marked in the image.
The PCB consists of four layers and has over 200 components. The jumpers are used for bypassing the second stage and hence connecting the first stage directly to the output.

3 Results and conclusion

In this section, all the measurements, as well as the calculated values regarding the noise analysis, will be described. The simulation of the prototyped LNA is done with the LT-spice

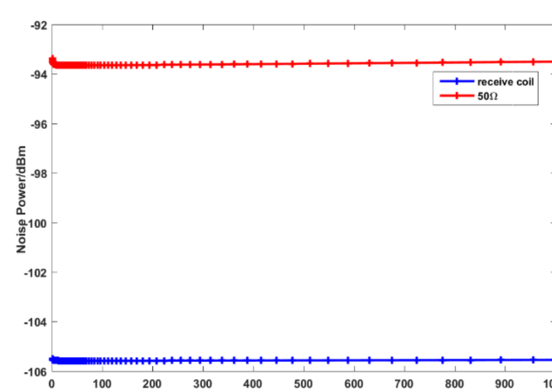

Figure 4: Simulated noise power of the prototyped LNA.

(from Linear Technologies). The noise power of the prototyped LNA is calculated by simulated input noise with the termination of 50 Ω as well as with a receive coil and is shown in **Figure 4**.

For measurement of the noise power, all the measurements are performed by the measurement setup described in section 2.1. For comparison purpose, the device under test (DUT) is switched between the prototyped LNA and the commercially available LNA. For simplification purposes, not all the measurements are shown but all the calculated values such as input noise, output noise, and NF are shown in Table 1. **Figure 5** shows the noise performance of the prototyped LNA with gains of 105 and 500, with input termination with a 50 Ω resistor.

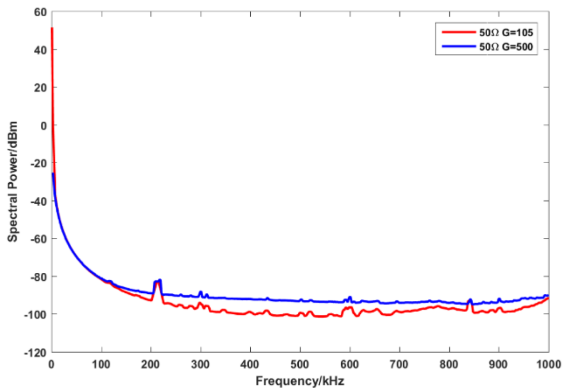

Figure 5 : Simulated noise power of the prototyped LNA with 50 Ω termination.

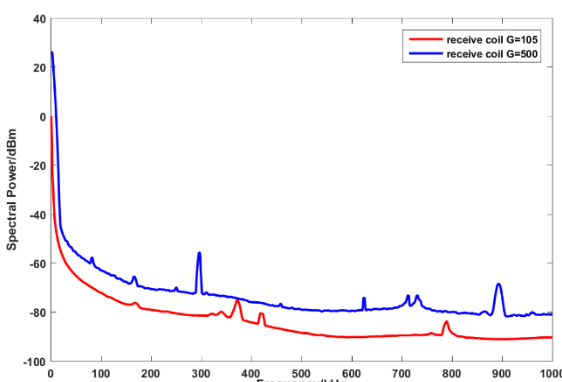

Figure 6: Simulated noise power of the prototyped LNA terminated with a coil as described in section 2.1.

Similarly, **Figure 6** shows the performance of the LNA with input termination with a receive coil. The receive coil has an internal resistance of approx. 0.551 mΩ, a self-capacitance of approx. 2.5 pF and inductance of approx. 130 µH. From the above data, an in-built function present in the spectrum analyzer for calculating the spectral noise density in dBm/Hz is used. For further comparison, these values are also measured with the commercially available LNA. And the equations described in section 1.1 are used for calculating input noise, output noise as well as NF. These values are stated in **Table 1**.

Table 1: Spectral density, input noise, output noise and the NF of the prototyped LNA and commercially available LNA.

	Input	G	Spectral Density in dBm/Hz	Input Noise in nV/√Hz	Output Noise in µV/√Hz	NF in dB
Prototyped LNA	50 Ω	105	-128.549	0.795	0.0834	5.30
		500	-116.712	0.653	0.326	3.32
	Coil	105	-120.419	0.223	0.022	13.58
		500	-118.670	0.546	0.273	1.35
Commercially available LNA	50 Ω	100	-108.43	8.4	0.84	25.57
		500	-93.65	9.2	4.64	26.37
	Coil	100	-107.266	1.01	0.10	26.73
		500	-92.90	1.06	0.53	27.11

In the current research, a prototyped LNA is designed and manufactured for MPS. Moreover, the prototyped LNA is compared with a commercially available LNA. The prototyped LNA has an input noise of 546 $pV/\sqrt{Hz}$ and NF of 1.35 dB with a receive coil at input. The NF is approx. 25 times lower than the NF of the commercially available LNA in the same scenario.

Author's Statement

Research funding: The authors state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent is not applicable. Ethical approval: The conducted research is not related to either human or animals use.

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