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Highly symmetric filter for a fully differential receive chain

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Abstract

Differential signaling can provide a higher fidelity of the receive signals in MPI, which is especially important for mobile scanner setups not being operated in a shielding room. A passive, highly symmetrical filter is presented as a part of the fully differential receive chain of the scanner setup. Due to the combined use with a gradiometric receive coil, the requirements for the components in terms of voltage and current specifications can be lowered which allows for partly building the filter on a PCB with well-matched SMD capacitors and trace lengths. The achieved attenuation for the differential-mode excitation field feedthrough is 77 dB while providing a common-mode rejection of more than 49 dB throughout the receive bandwidth.

I Introduction

The aim of our preclinical MPI system based on a permanent magnet based field free line (FFL) [1] is the creation of a mobile scanner featuring a high spatial resolution combined with very high sensitivity. Due to the requirement of mobility, the scanner cannot be placed in a shielded room and therefore, the signal integrity has to be assured by other means. While rigorous shielding of both field generator and cable paths, as well as linear power supplies and specific EMI countermeasures for various components are in place, we still want to go a step further and implement a fully differential receive chain in order to attenuate common-mode interference. For this purpose, maintaining symmetry throughout the signal chain is of key importance since both signal paths should influence the signal in the same fashion. A fully differential low noise amplifier for the system is presented in [2], while the symmetric filter for attenuating the feedthrough of the excitation field is discussed in this research.

II Material and methods

The scanner uses a single solenoid coil of 150 mm for both excitation and focus field [3] and therefore features excellent homogeneity while allowing for 3D images by mechanically rotating the FFL and moving the sample through the bore. The homogeneity allows for a strong attenuation of the feedthrough by means of a gradiometric receive coil, which makes higher-order filters redundant. Consequently, a fourth-order notch filter is sufficient. Due to the lower number of components, maintaining the symmetry can be achieved with a lower effort compared to higher filter orders necessary for filter-only systems.

In order to achieve a maximum common-mode rejection ratio (CMRR) in the subsequent LNA, the component values should be as equal as possible. The low voltages in the filter allow for using SMD capacitor and therefore we decided to use a PCB for mounting the capacitors. Due to their very low ESR and ESL values combined with high stability of the capacitance value, MLCC capacitors with a U2J dielectric are chosen. For achieving a high Q without magnetic cores, the inductors are cho-

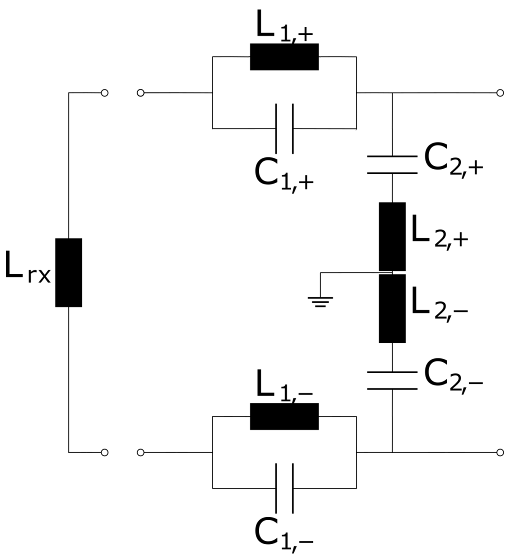

Figure 1: Schematic of the symmetric filter and the receive coil (L_{rx}).

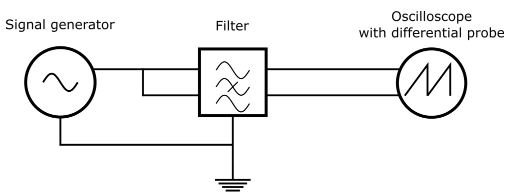

Figure 2: Schematic of the measurement setup for the CMRR measurement.

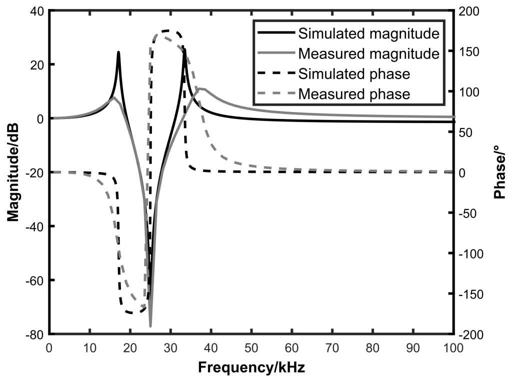

Figure 3: Frequency response comparison between the simulated and the prototyped filter. In order to adjust for the single ended nature of the network analyser, the simulation has been changed accordingly.

sen to be built as external parts and then to be connected to the PCB.

The design procedure for the filter is based on the requirements for feedthrough attenuation and attenuation of the higher harmonics. With an LTSpice XVII (Analog Devices, Inc., MA, USA) simulation, a rough estimate of appropriate values for attenuation of more than 70 dB is performed according to the schematic as shown in Fig. 1. Only a single component shall be used for every capacitance in the filter in order to minimize tolerances. In order to facilitate the selection process of matching capacitors, all resonance circuits shall feature the same nominal capacitance. In this case a capacitance of 150 nF (C1210C154J1JACAUTO, KEMET Electronics Corporation, SC, USA) is chosen, which corresponds to 270.2 μH per inductor at the excitation frequency of 25 kHz. The capacitors are sorted and with the values of the selected pairs the needed inductances are recalculated and then geometrically optimized according to the findings in [4].

For partly decoupling resistance and inductance, the toroidal cores for $L_{1,\{+,-\}}$ are designed as split air cores with an adjustable air gap. The inductance can then be easily adapted to the capacitance in order to create resonance at the excitation frequency, while the resistance stays almost the same since the wire length does not change and the proximity effect is of minor influence here. The inductors $L_{2,\{+,-\}}$ are built with a single split ferrite core (T400-2D, Micrometals Inc., CA, USA) with a center tap. The combination of air cores in the parallel resonance parts and magnetic cores in the series resonance parts ensures high linearity while maintaining a low signal drop due to the higher Q factor in the second stage. The winding forms are then 3D printed and wound with 400x0.05 mm Litz wire (Elektrisola Dr. Gerd Schildbach GmbH&Co. KG, Germany).

After assembly, the frequency response is measured with a network analyzer (E5061B, Agilent Technologies, Inc., CA, USA). The CMRR is determined as depicted in Fig. 2 by supplying a common-mode voltage to the filter by a function generator (DG1032, RIGOL Technologies, Inc., China) and measuring the output voltage with a differential probe and an oscilloscope (ZD1000 and HDO6104-MS, Teledyne LeCroy, NY, USA).

III Results and discussion

Twenty capacitors are measured and sorted with the help of an LCR Meter (E4980A, Agilent Technologies, Inc., CA, USA) and two pairs are selected. All tolerances were positive with an average capacitance of 155.5±1 nF. The capacitance of the pair for $C_{1,\{+,-\}}$ is chosen to be 155.0 nF, whereas the pair for $C_{2,\{+,-\}}$ is chosen to have 155.3 nF. This findings hint, that the capacitors should always be measured prior to planning the inductors.

The resulting inductances $L_{1,\{+,-\}}$ are trimmed by removing a few windings in order to match their resistance and then mounted on their fixtures. The resulting values with a minimal air gap are $L_{1,+} = 265.3$ μH with a resistance of 644 mΩ and $L_{1,+} = 267.9$ μH with a resistance of 648 mΩ. The percentage difference of the resistances is 0.6 %. With the help of the movable inductors, the individual resonance circuits are easily tuned to the excitation frequency. A comparison of the resulting frequency response is depicted in Fig. 3.

The LTSpice simulation of the filter adjusted to the measured values of inductance and capacitance predicts an attenuation of 75 dB at the excitation frequency, while the measurement shows an attenuation of 77 dB. The slight difference can be attributed to stray capacitances, which can also explain the dampened overshoot around the notch.

The CMRR at power line frequency is not measurable within the accuracy of the test setup and at 25 kHz the attenuation is 90 dB. For the predominant interference in our lab of around 1 MHz still an attenuation of 49 dB is achieved. The measured CMRR values all have to be taken with caution since the datasheet of the differential probe states a CMRR of 60 dB at line frequency and 30 dB at 20 MHz.

Interestingly, the differential-mode attenuation in the passband of the simulated filter is around 1.5 dB whereas the measurement indicates near to zero attenuation.

IV Conclusions

The described symmetric filter provides a high CMRR and stopband attenuation while negligibly affecting the higher harmonics. Due to the higher interference suppression and the doubled output swing, the sensitivity of the receive chain should increase. This has yet to be validated within the scanner setup and will be subject to future research.

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Author's Statement

Authors state no conflict of interest.

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