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An Inductorless Wideband Balun-LNA for Spin Torque Oscillator-based Field Sensing

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Abstract—This paper presents a wideband inductorless Balun-LNA targeting spin torque oscillator-based magnetic field sensing applications. The LNA consists of a CS stage combined with a cross-coupled CG stage, which offers wideband matching, noise/distortion cancellation and gain boosting, simultaneously. The Balun-LNA is implemented in a 65 nm CMOS technology, and it is fully ESD-protected and packaged. Measurement results show a bandwidth of 2 GHz - 7 GHz, a voltage gain of 20 dB, an IIP₃ of +2 dBm, and a maximum NF of 5 dB. The LNA consumes 3.84 mW from a 1.2 V power supply and occupies a total silicon area of 0.0044 mm². The measurement results demonstrate that the proposed Balun-LNA is highly suitable for the STO-based field sensing applications.

I. INTRODUCTION

Nowadays, magnetic field sensors are used in a wide range of applications, including but not limited to navigation, brain wave detection, vehicle disturbances, as well as measuring generated field from electric currents [1]. Hall-effect sensors are transducers that yield an output voltage in regards to a magnetic field, and they are widely used. They feature miniature size, low cost, fast switching time, high reliability and good durability [2]. However, they have a limited sensitivity of 15 mV/G (=15 mV/Oe in free space) [2], and require a sensing system with a large signal-to-noise ratio (SNR). Recently, the spin torque oscillator (STO) technology shows the potential to overcome these issues, and to be used as field sensor [3]. Unlike Hall-effect sensors, the STO-based sensors translate the magnitude and angle of the magnetic field into oscillation frequencies instead of voltage levels. Accordingly, the STO-based sensors are less sensitive to noise. In addition, STOs offer higher resolution of field sensing, compared to Hall-effect field sensors. For instance, as reported in [3], a magnetic field change of one oerstad (Oe) can bring 173 MHz change in the oscillation frequency of the STO. Similarly, a change of field angle by one degree can change the frequency by 500 MHz [4]. Moreover, STOs have low power consumption and high level of integration with CMOS technologies [5].

In STOs, the voltage oscillations are produced by two spintronic effects: spin transfer torque and magnetoresistance (MR) [6]. Based on the barrier material, an STO is either a magnetic tunnel junction (MTJ) type or a giant magnetoresistance (GMR) type. This work focuses on the

Figure 1: MTJ STO-based sensing system

MTJ STO since it provides higher output power, hence it is more suitable for applications. An MTJ STO-based sensing system can be built as shown in Fig. 1. This system is composed of an MTJ STO, a bias-tee, a wideband low-noise amplifier (LNA), buffers and a frequency-voltage converter (FVC). The bias-tee allows only the AC oscillation signal passing to the LNA, without being disturbed by the DC biasing current required to drive the MTJ STO. The wideband LNA is required to mitigate the limited output power generated by the MTJ STO, so that the amplified signal can be directly utilized by an FVC. Buffers are required at the output of the LNA for driving the FVC. An FVC converting the frequencies into voltages, which allows convenient processing, is required to complete the system. In this system, the LNA is a key component, since it should provide sufficient gain within a large frequency range, while consuming low power and area, so that it can be used in a wide range of sensing applications. As a first step to build the MTJ STO-based sensing system, this paper focuses on the dedicated wideband LNA.

II. LNA SPECIFICATIONS

In this work, an MTJ STO similar to those in [7] is used. The oscillation frequency of the MTJ STO can be tuned between 3 GHz and 8.5 GHz by altering the magnetic field magnitude from 100 Oe to 1000 Oe, as it can be seen in Fig. 2(a). The sensitivity of the MTJ STO is approximately 6.11 MHz/Oe. Considering that extra tunability can be obtained by varying the magnetic field angle and the injected DC current, the bandwidth of the LNA should cover 2 GHz - 8.5 GHz (with margin) to take full use of the STO's tunability.

As mentioned before, the MTJ STO is operating under the MR effect, giving a periodic resistance change as

Figure 2: (a). MTJ STO operation frequency as a function of the magnetic field; (b). Measured MR of the STO

explained in [7], and depicted in Fig. 2(b). R_P and R_{AP} in Fig. 2(b) are the measured minimum and maximum resistances of the MTJ STO, when the magnetizations of the free layer and polarizing layer are in parallel and anti-parallel alignments, respectively. During the operation, the resistance of the MTJ STO changes within a fraction of the range from $R_P = 38 \Omega$ to $R_{AP} = 64 \Omega$, and with a period of several hundreds of picoseconds. To maximize the power delivered from the MTJ STO to the LNA, the input impedance of the LNA should be matched to the impedance of STO (Z_S). Nonetheless, this periodic variation of Z_S cannot be dynamically matched, resulting in time-variant noise and input impedance matching conditions. Particularly, the time-variant impedance matching is of great importance in this case since it directly affects the signal power delivered to the LNA. As a result, the impact of Z_S , which takes value within $51 \Omega \pm 13 \Omega$ (under all possible conditions), on the input impedance matching of the LNA is considered and analyzed. The input impedance matching can be characterized by the input reflection coefficient (Γ_{in}) and it is expressed by:

$$\Gamma_{in} = \frac{Z_{IN} - Z_S}{Z_{IN} + Z_S} = \frac{\mp 14 \cdot \cos(2\pi f \cdot t)}{100 \pm 14 \cdot \cos(2\pi f \cdot t)} \quad (1)$$

where Z_{IN} is the input impedance of the LNA, which should be matched to $(R_P + R_{AP})/2 = 51 \Omega$. The impact of the periodic resistance on the reflection coefficient is found by evaluating Eq. (1) for Z_S values ranging from 38Ω to 64Ω . It can be calculated that in one oscillation period, the maximum Γ_{in} is 0.1628, which shows a maximum mismatch loss ($= -10 \cdot \log(1 - \Gamma_{in}^2)$) of 0.12 dB. Accordingly, this small variation in mismatch loss indicates that the periodic resistance change has an insignificant impact on the impedance matching. Additionally, it suggests that the input impedance of the LNA should be matched to $(R_P + R_{AP})/2$.

To achieve the sensing system proposed in Fig. 1, a wideband LNA is required to enhance the STO's limited output power of about -40 dBm to a level of about -30 dBm, which can be handled by an integrated FVC with a topology similar to [8]. Considering the voltage division due to the impedance matching (6 dB loss) and

the required gain of 10 dB, a wideband LNA with a voltage gain larger than 16 dB is required. In addition, in view of the signal loss on the output buffer and non-ideal wideband impedance matching, an additional margin of gain is highly desired. To fully use the wide tunability of the MTJ STO for a wide field-sensing range, a bandwidth of 2 GHz - 8.5 GHz is needed. Furthermore, in order to achieve an accurate field sensing system, the LNA should provide good linearity. Specifically, the input-referred 1 dB compression point of the LNA should be much greater than the amplitude of the MTJ STO signal. Moreover, the LNA should be inductorless, ESD-protected, packaged and have a low power consumption, making the proposed MTJ STO-based sensing system suitable for a wide range of applications.

As explained before, the STO-based sensor is noise-resistant. Consequently, the noise performance of the wideband LNA is not very critical in this case. As a result, an LNA with a noise performance that is similar to the state-of-the-art LNA [9] in this frequency range, is desired.

To obtain the wideband impedance matching as well as good linearity without using additional circuitry and extra power, the Balun-LNA [10] is a suitable topology so that it will be used in the MTJ STO-based sensing system. Moreover, thanks to the on-chip Balun, the differential output with buffers can be directly used by an integrated FVC. However, the existing CG-CS Balun-LNAs [9-11] suffer from the trade-offs between power consumption, noise figure (NF), bandwidth, voltage gain and gain balancing. This work presents a wideband Balun-LNA, which offers more degrees of freedom to enhance the Balun-LNA performances targeting the MTJ STO-based sensing systems.

III. BALUN-LNA

An inductorless Balun-LNA, which is based on the topology given in [12], is proposed for MTJ STO-based field sensors. The Balun-LNA is illustrated in Fig. 3 and it consists of a CS stage (M_1) combined with a cross-coupled CG stage (M_2, M_3). Unbalanced-to-balanced conversion is accomplished in the CS and CG stages, which amplify the unbalanced input with equal gain, yet yield output voltages with opposite signs. By cascoding the transistor M_1 with M_3 , this circuit topology is able to boost the voltage gain while enhancing the bandwidth by reducing the Miller effect. Moreover, the dual feedback loop introduced by the cross-coupled transistors mitigates the trade-offs between gain balancing, impedance matching and noise performance, which were found in similar topologies [9-11]. For the proposed Balun-LNA, the conditions for gain balance, impedance matching ($Z_{IN} = R_S$) and noise/distortion cancellation are given by:

$$\frac{R_1}{R_2} = \frac{g_{m3}}{g_{m2}} \quad (2)$$

$$g_{m2} = \frac{1}{\frac{g_{m1} \cdot r_{o1} + 1}{g_{m3} \cdot r_{o1} + 1} \cdot R_S} \quad (3)$$

Figure 3: The proposed dedicated Balun-LNA

Figure 4: Chip photo of the proposed Balun-LNA

$$\frac{R_1}{R_2} = \frac{g_{m1} \cdot r_{o1} + 1}{g_{m3} \cdot r_{o1} + 1} \cdot g_{m3} \cdot R_S \quad (4)$$

where g_{m1} - g_{m3} are the transconductances of M_1 - M_3 and r_{o1} is the drain-source resistance of M_1 . When Eq.(2) - (4) are fulfilled, the input impedance matching, noise/distortion cancellation, gain boosting and gain balance can be achieved simultaneously. Accordingly, the proposed Balun-LNA decouples the trade-offs between gain, bandwidth, power consumption, NF and silicon area. To provide the ESD protection, two diodes are added at both input and output pads. Afterwards, the Balun-LNA is further optimized to provide input matching, and to achieve sufficient gain and bandwidth, considering but not limited to the following factors: ESD diodes, parasitics introduced by physical implementation and packaging.

The proposed Balun-LNA requires a balanced-to-unbalanced output buffer for measurement purpose, as shown in Fig. 3. The output buffer offers a gain close to 1 and is designed to drive the 50 Ω impedance of the measurement setup. Besides, an MIM capacitor of 1 pF is placed in series with the output signal to provide AC coupling. In order to evaluate the performance of the core LNA, the losses introduced by the buffer and the capacitor are estimated and de-embedded from the measurement. The proposed Balun-LNA is implemented in a 65 nm CMOS process with a 1.2 V power supply. The post-layout simulations of the Balun-LNA core exhibit a -3 dB bandwidth of 2 GHz - 8.7 GHz, a voltage gain of 20 dB, and an IIP₃ of approximately -1 dBm. The buffered Balun-LNA gives a maximum NF of 4.5 dB within the -3 dB bandwidth. Simulation results show that the ESD diodes

have trivial impact on performance metrics. The results further meet the specifications determined in section II.

IV. MEASUREMENT RESULTS

The chip photograph of the prototype is shown in Fig. 4. The Balun-LNA core occupies an area of 0.0044mm², and consumes 3.84 mW from a 1.2 V power supply. To measure the performance of the proposed Balun-LNA, the die was directly wire-bonded on the PCB with ROGERS 4350 high-frequency substrate. The RF input and output are connected to 50 Ω microstrip transmission lines, where SMA connectors are attached.

Figure 5 presents the simulated and measured S₂₁ and S₁₁. Additionally, the simulated and de-embedded voltage gain of the Balun-LNA are shown. The measured S₂₁ is in agreement with the post-layout simulation, yet it is not flat within the frequency range of interest. This is caused by the signal discontinuities on PCB traces, SMA connectors, bond wires, as well as limited PCB foil roughness and skin effect at high frequencies. To obtain the voltage gain of the Balun-LNA core, 6 dB are added to the measured S₂₁, considering the loss of the output buffer (it halves the output voltage with a matched load). In addition, the output series AC coupling capacitor together with the load forms a voltage divider. The frequency dependent loss introduced by this AC coupling capacitor should also be removed from the S₂₁, so as to estimate the performance of the LNA core. After de-embedding these losses, a voltage gain of 20 dB and a -3 dB bandwidth of 2 GHz - 7 GHz are obtained. Although there is a bandwidth shrinkage of 1.7 GHz, the Balun-LNA can still cover a large portion of the MTJ STO's operation frequency range. The bandwidth shrinkage issue, fortunately, can be alleviated by integrating the entire sensing system on-chip, which avoids the signal degradation introduced by the PCB.

At the input, a π -network is formed by the bondwire inductance (~ 1 nH) together with the on-PCB (~ 300 fF) and on-chip (~ 100 fF) capacitances. This π -network offers a decent impedance matching (S₁₁ < -10 dB) hence efficient power transfer between 5.25 GHz and 7 GHz. Below 4 GHz, however, a degradation of the measured S₁₁ is observed. This degradation is due to the 1 pF AC coupling capacitor at the input, which has brought non-negligible impedance at low frequencies. This capacitor has been employed for measurement purposes and it can be avoided in the real applications, since a bias-tee (Fig. 1) would be used between the STO and the LNA.

The NF is measured by using Y-factor method combined with a *Mini-Circuits ZVE-3W-83+* amplifier, which provides 35 dB gain over 2 GHz - 8 GHz bandwidth. The simulated, measured and de-embedded NFs of the buffered Balun-LNA are depicted in Fig. 5. Since the buffered Balun-LNA has a limited voltage gain, the noise contribution of the *Mini-Circuits ZVE-3W-83+* to the measured NF is significant and should be de-embedded from the measured NF. For simplicity, the de-embedding

Figure 5: Measured and simulated S21 and S11, simulated and de-embedded voltage gain of the Balun-LNA core

Figure 6: Measured, simulated and de-embedded NF

is done by assuming that the impedances at both input and output are matched. The maximum de-embedded NF of the buffered Balun-LNA is 5 dB, which is 0.5 dB larger compared to the post-layout simulated NF. This noise performance degradation and fluctuation are caused by the gain variation, impedance mismatch, on-chip and off-chip parasitics, and other losses in the signal path.

Finally, the measured input-referred 1 dB compression point is about -13 dBm and the IIP₃ is +2 dBm. The measurement results meet the linearity specification determined in section II. Additionally, they prove that the proposed Balun-LNA topology offers the non-linear distortion cancellation.

Table I summarizes the performance of the proposed Balun-LNA and gives comparison to other recently published Balun-LNAs [9-11,13]. Among all the designs, the proposed Balun-LNA presents the largest gain and bandwidth product. Moreover, it shows competitive linearity and comparable NF within a wider frequency range. Furthermore, this Balun-LNA occupies a very small chip area and offers low power consumption. The measurement results validate the analysis results given in section III.

V. CONCLUSION

A Balun-LNA topology targeting MTJ STO-based field sensing applications has been presented in this paper. The proposed Balun-LNA was implemented in a 65 nm CMOS technology and the measurement results show a voltage gain of 20 dB, bandwidth of 2 GHz - 7 GHz, IIP₃ of +2 dBm, and noise figure below 5 dB, while

Table I: Comparison with previous Balun-LNA designs

	Tech (nm)	VDD (V)	BW (GHz)	Gain (dB)	NF (dB)	IIP ₃ (dBm)	S11 (dB)	Power (mW)
This work	65	1.2	2-7	20	<5	+2	-6	3.84
[9]	180	1.1	3.1-10.6	11.02	<4.9	-3.6	-10	6.93
[10]	65	1.2	0.2-5.2	15.6	<3.5	0	-10	14
[11]	130	1.2	0.1-2	16.6	<3.8	+0.5	-10	3
[13]	130	1.3	6.5-9	23	<3.2*	-18.4	-20	7.15

*Post-layout simulation result

consuming only 3.84 mW from a 1.2 V power supply. Without the need of inductors, the Balun-LNA is very compact and occupies a total area of only 0.0044 mm². The measurement results demonstrate that the dedicated Balun-LNA has the potential to be used in MTJ STO-based field sensing systems.

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