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Design of a CMOS integrated on-chip oscilloscope for spin wave characterization

Eugen Egel,[1,a] Christian Meier,[1] György Csaba,[2] and Stephan Breitkreutz-von Gamm[1]
[1]*Institute for Technical Electronics, Technical University of Munich, Munich, Germany*
[2]*Center for Nano Science and Technology, University of Notre Dame, Notre Dame, Indiana, USA*

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Spin waves can perform some optically-inspired computing algorithms, e.g. the Fourier transform, directly than it is done with the CMOS logic. This article describes a new approach for on-chip characterization of spin wave based devices. The readout circuitry for the spin waves is simulated with 65-nm CMOS technology models. Commonly used circuits for Radio Frequency (RF) receivers are implemented to detect a sinusoidal ultra-wideband (5-50 GHz) signal with an amplitude of at least 15 μV picked up by a loop antenna. First, the RF signal is amplified by a Low Noise Amplifier (LNA). Then, it is down-converted by a mixer to Intermediate Frequency (IF). Finally, an Operational Amplifier (OpAmp) brings the IF signal to higher voltages (50-300 mV). The estimated power consumption and the required area of the readout circuit is approximately 55.5 mW and 0.168 mm^2, respectively. The proposed On-Chip Oscilloscope (OCO) is highly suitable for on-chip spin wave characterization regarding the frequency, amplitude change and phase information. It offers an integrated low power alternative to current spin wave detecting systems. [http://dx.doi.org/10.1063/1.4975367]

I. INTRODUCTION

Spin wave based devices, one of the promising candidates for beyond-CMOS computing, provide both Boolean and non-Boolean data processing for high-frequency and low power applications.[1–4] An energy efficient way to perform a Fourier transform can be realized with the spin wave lens by varying the applied magnetic field in a bi-convex manner.[1] Before the spin wave devices become practically useful more investigation of the spin wave characteristics has to be done.

Spin wave devices inherently operate at high frequencies (5-50 GHz),[5] which makes signal processing faster but complicates the analysis of the measured signal. Current spin wave detectors require external network analyzers connected to wave guides. However, on-chip sensing is still necessary for practical applications. Due to the integration challenge of the whole system, on-chip sensing of the spin waves has not been demonstrated yet.

Here we show a concept of the CMOS integrated On-Chip Oscilloscope (OCO) containing a suitable sensor and readout circuit, simulated in 65-nm CMOS technology, to detect and characterize spin-waves in the 5-50 GHz range (Figure 1a). On the long run the integrated characterization of the spin waves can be tailored for a low power and low cost alternative compared to currently used spin wave detecting systems.

This paper is organized as follows. First, we describe the modeled loop antenna, as a spin wave detector, in Section II. The on-chip readout circuitry for spin wave characterization is presented in Section III. Here we show the simulation results and the implemented circuit topologies of the LNA,

[a]Electronic mail: eugen.egel@tum.de

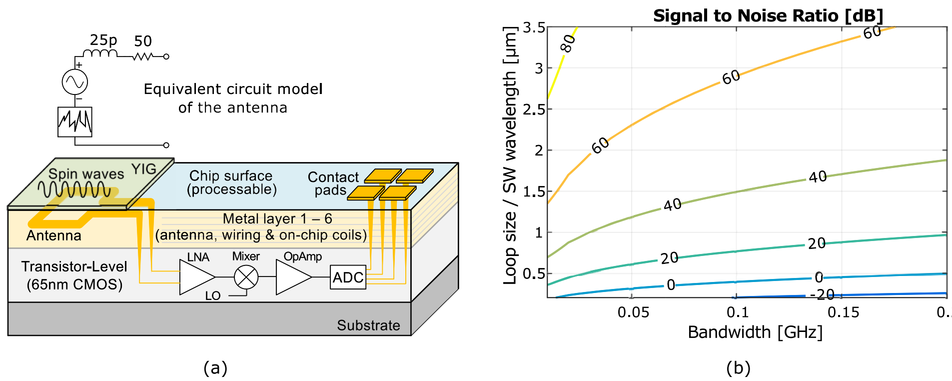

FIG. 1. Concept of the spin wave on-chip detection developed in 65-nm CMOS technology and equivalent circuit model of the antenna (a). SNR of the antenna depending on its size and the OpAmp bandwidth (b).

mixer and Operational Amplifier (OpAmp). In Section IV we discuss the concept for integrated characterization of the spin wave devices and summarize the paper.

II. LOOP ANTENNA AS A SPIN WAVE SENSING ELEMENT

There are several spin wave sensors such as Giant Magnetoresitance (GMR) or Tunnel Magnetoresistance (TMR) devices. We pursue the realization with the integrated loop antennas, since they provide a low resistivity (50 Ω) and a scalable sensing area. The restriction for the antenna size would be half of the spin wavelength. The loop antenna can be located above or below an insulating magnetic medium such as Yttrium-Iron-Garnet (YIG).[5] The equivalent circuit model of the loop antenna, required for a simulation of the whole system, is depicted in Figure 1a. We use an approach described in[6] to figure out the serial resistance and inductance of the loop antenna.

Micro magnetic simulations, using OOMMF,[7,8] (Figure 1b) indicate that an antenna with an area of 1 μm^2 can recover signals, restricted to a 100 MHz bandwidth, at an amplitude of a few tens microvolts (-80 to -90 dBm) and with a signal-to-noise ratio of 20-40 dB. The thermal agitation of the magnetic moments is negligible compared to the thermal noise of the 50 Ω loop resistance, since the equivalent resistance of the magnetic noise is in the range of 1 mΩ.[5]

III. CONCEPT FOR SPIN WAVE ON-CHIP DETECTION

Our concept of the on-chip spin wave sensing is based on widely used RF receivers. The readout circuitry is depicted in Figure 1a. The spin wave signal, generated by the spin wave device, is picked up by the loop antenna, that is integrated in the top metal layer. The electrical signal induced in the

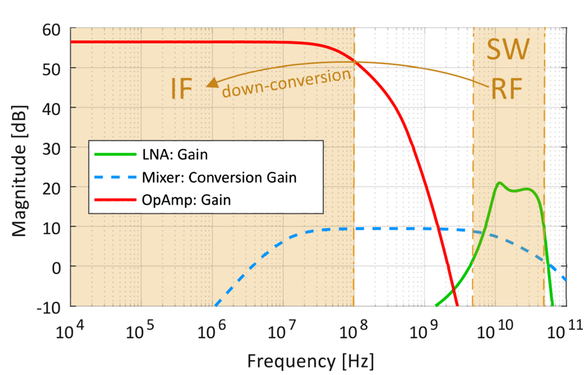

FIG. 2. Simulated gain of the LNA, mixer and OpAmp.

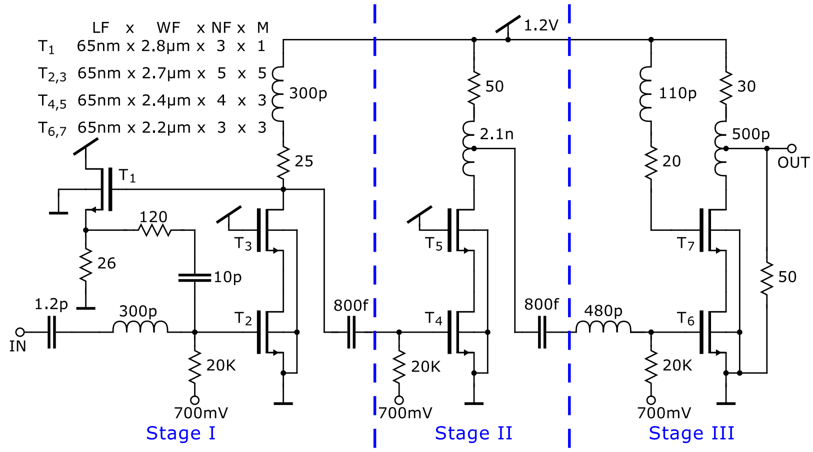

FIG. 3. Topology of the LNA with a 20 dB gain between 10-40 GHz.

loop antenna is amplified by an ultra-wideband LNA, which amplifies the signal by 20 dB in the 10-40 GHz frequency range (Figure 2). Based on the approach of,[9] a relatively flat gain of the LNA is achieved with an inductive peaking technique, consisting of three amplifying stages with shifted center frequency. The topology of the developed LNA and the dimensions of its components are presented in Figure 3. The estimated power consumption and area of the LNA are equal to 41.8 mW and 0.143 mm^2, respectively. Of this area, about 95% is attributed to the inductors.

In order to enhance the amplified RF signal to reasonably high voltage values, first it has to be down-converted by a mixer to lower IF, i.e. multiplication of both the RF and Local Oscillator (LO) signals in the time domain or convolution in the frequency domain. For the mixer we have achieved a Conversion Gain (CG) of 9 dB at 5 GHz attenuating to 1 dB at 50 GHz (Figure 2). To have a more flat curve of the CG in the band of interest, the area hungry inductors can be implemented for compensating the parasitic capacitances of the transistors. The topology of the designed mixer is shown in Figure 4a, which has been already realized by[10] in 0.13-μm CMOS technology. For the power consumption of the mixer we calculated 10.4 mW. The area, without taking the ideal baluns into account, is 1.12×10^{-3} mm^2.

For the above mentioned down-conversion, the mixer needs a LO signal. By sweeping the LO frequency and observing the IF signal, the frequency of the RF signal is detected. In our simulations we used an ideal voltage source for generating the LO signal. However, one can implement a digitally tunable on-chip frequency synthesizer as described in,[11] which consumes 3.3 mW and 24.6×10^{-3} mm^2.

The output signal of the mixer contains both high and low frequency components (Figure 5a), due to a multiplication of the periodic RF and LO signals in the time domain or a convolution

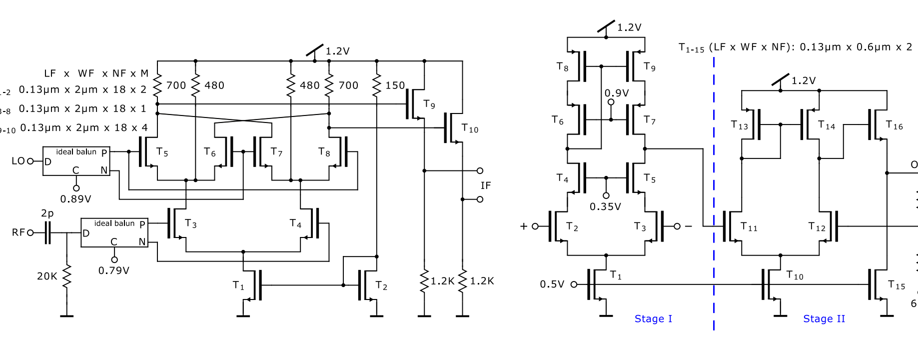

FIG. 4. Topology of the developed mixer (a) and operational amplifier (b).

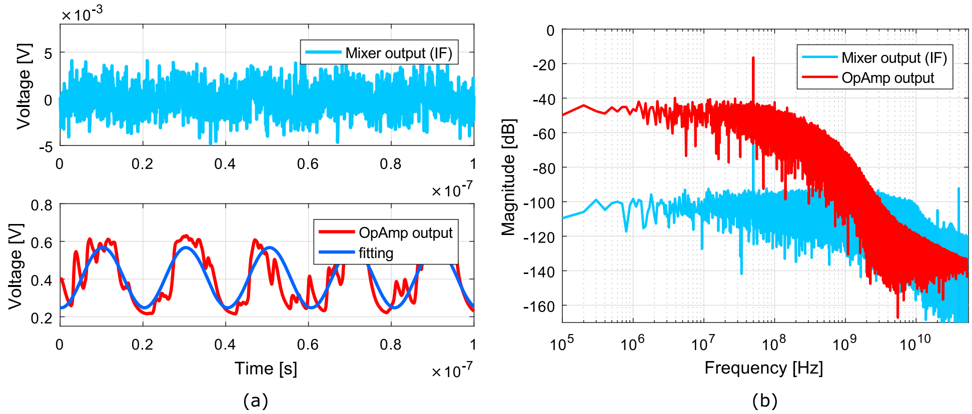

FIG. 5. Transient response (a) and frequency response (b) of the mixer and operational amplifier output signals.

in the frequency domain. By applying the IF signal to the OpAmp with a low pass characteristic, the unnecessary high frequency components of the IF signal are filtered out. The topology of the designed two stage OpAmp is sketched in Figure 4b. The OpAmp with a gain higher than 50 dB up to 100 MHz increases the amplitude of the IF signal to higher voltages. Compared to other components, the OpAmp has a relatively lower power consumption of 75.6 μW and a smaller chip area of 14.3 μm^2.

Finally, the amplified signal has to be converted by an Analog-to-Digital Converter (ADC) in order to enable an external or on-chip digital analysis of frequency, amplitude variation and phase information of the spin wave devices. The estimated power consumption and area of the whole readout circuitry is equal to 0.39 mW and 0.17 mm^2, respectively.

Figure 5a shows the transient analysis of the OpAmp output signal demonstrating the reconstruction of the spin wave signal in the proposed readout circuitry. For the simulation we assumed a sinusoidal signal, induced in the loop antenna, with an amplitude of 30 μV and frequency of 20 GHz. The sinusoidal LO signal is set to 1 dBm and 20.05 GHz. The reasonably high amplitude of more than 160 mV and a relatively low frequency of 50 MHz at the fitted output of the OpAmp can easily be read out as shown in Figure 5a.

Figure 5b demonstrates the spectrum of the mixer and OpAmp output signals. The amplification of the low frequency components and damping of the high ones are obvious. Besides, the applied frequency difference between the LO and the RF signal of 50 MHz stands out in the spectrum plot.

The simulation results are valid for room temperature (300 K) with a supply voltage of 1.2 V. For low resistances, nonsalicided N+ or P+ poly resistor RF models are used. High resistances are simulated with nonsalicide high ρ (1000 Ω/sq) poly resistor RF models. We use Metal-Insulator-Metal (MIM) RF capacitor models with a p-type substrate underneath. For the initial approximation we used ideal inductors and ideal transformers/baluns in the readout circuitry. Simulations are performed in Cadence Virtuoso with 65-nm technology node, provided by United Microelectronics Corporation (UMC).

IV. DISCUSSION AND CONCLUSION

Spin wave devices are one of the promising candidates for fast yet low power computing and signal processing tasks. The presented OCO is highly suitable for on-chip spin wave characterization and offers an integrated low power alternative to current spin wave detecting systems.

The developed LNA has a gain of 20 dB in the frequency range of 10-40 GHz. The mixer shows a conversion gain of 1-9 dB in the frequency range of 5-50 GHz. The operational amplifier has a gain of 56 dB and a corner frequency of 70 MHz. The total gain of the OCO in the frequency band of interest is between 70 and 85 dB. The signal-to-noise ration at the OpAmp output is equal to 1.25 dB. At the point is worth mentioning that the frequency of the IF signal (50 MHz) still detectable, due to more than 20 dB magnitude difference compared to other frequency components. Total costs for the readout circuitry are estimated at 55.5 mW and 0.17 mm^2, which are relatively low for a microwave processing device.

Initial simulations show that integrated on-chip detection of the spin waves is possible and the goal of the realization should be pursued further. However, more investigation is required and the ideal inductor model should be replaced with realistic ones. The frequency dependent inductor values and the parasitic serial resistances can dampen the OCO performance at high frequencies. Moreover, one of the biggest challenges of proposed concept that remains is the realization of the magneto-electric interface.

By using the spin wave devices for on-chip computing at a specific frequency, the readout circuitry can be designed for this certain frequency and optimized further, hence the power and area consumption will decrease even more. Moreover, the OCO could be readily adapted for magneto-resistive or spin hall effect sensing and even simplify its requirements. OCO is simple technique for spin wave characterisation that can be widely used for several applications.

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