A 28 GHz Superregenerative Amplifier for FMCW Radar Reflector Applications in 45 nm SOI CMOS

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Abstract—This paper presents the design and characterization of a 28 GHz integrated super-regenerative amplifier (SRA) in a 45 nm silicon on insulator (SOI) technology. The circuit is based on a complementary cross-coupled oscillator topology. The fabricated integrated circuit (IC) occupies an area of 0.67 mm^2 , and operates in a frequency range from 28.07 GHz to 29.35 GHz. Characterization results show the minimum input sensitivity of the circuit, as -85 dBm and the input power level corresponding to the linear to logarithmic mode transition as -66.3 dBm . The measured output power delivered into a 100Ω differential load is 1.1 dBm . The DC power consumption of the circuit is 10.6 mW . To the knowledge of the authors, the circuit has the best reported combined sensitivity and output power for an FMCW radar reflector implementation in CMOS.

Index Terms—millimeter wave integrated circuits; CMOS; FMCW radar reflector; Microwave applications

I. INTRODUCTION

Superregenerative amplifiers (SRA) make use of the regenerative sampling principle, where input signal amplification is achieved by a periodically quenched oscillator [1]. As illustrated in Fig. 1(a), the SRA receives an input signal at the passive resonator core and outputs an amplified signal at the same port, when a quench signal V_Q varies the transconductance across the resonator from positive to negative using an active device [1]. This process also results in a back radiation that needs to be suppressed in most circuits [1]. But key features of the circuit including low power consumption, extremely high gain and reduced system complexity makes it attractive for applications like mm-wave imaging [2], short-range wireless links for bio-medicine [3] and as back-scatter active reflectors for frequency modulated continuous wave (FMCW) radar and pulse radar systems as introduced in [4]. Radar reflector applications illustrated in Fig. 1(b), take advantage of the otherwise detrimental back radiated power. The FMCW radar sends out frequency chirps, the SRA samples these chirps in every quench cycle, and re-transmits back to the radar, resulting in increased measurement range [4].

Depending on whether the quenching signal saturates the output or not, the SRA can operate in either the linear mode or the logarithmic mode [1]. Several integrated logarithmic mode SRAs targeting radar reflector applications are found in literature with the terminology switched injection locked oscillator (SILO) [4] - [6]. While the design in [5] has high complexity and power consumption, the designs in [6] - [7] has lower output power and sensitivity. This work introduces a low

Fig. 1: (a) Block diagram of a generic SRA. (b) Illustration of SRA used as active reflector in a FMCW radar based system.

complexity differential cross-coupled oscillator based SRA implemented in 45 nm SOI technology, operating at millimeter-wave frequencies and optimized for combined sensitivity and output power with low DC power consumption.

The design of the SOI cross-coupled SRA is discussed in Section II. Characterization methodology and results are reported in Section III. Section IV summarizes the work by comparing the results with state-of-the-art FMCW active reflector implementations.

II. CIRCUIT DESIGN

The SRA is based on a CMOS complementary cross-coupled oscillator (CCO) as shown in Fig. 2. The frequency of oscillation f_{osc} is determined by the resonator inductance L_R and capacitance C_R as $f_{osc} = \frac{1}{2\pi\sqrt{L_R C_R}}$. $L_R \approx 150 \text{ pH}$ is implemented using a differential symmetrical inductor with an unloaded quality factor $Q_L \approx 30$, and optimized using electromagnetic (EM) simulations. The capacitance C_R is the sum of varactor capacitances, the effective capacitance in the feedback path of nMOS devices $M_{2,3}$, $C_{k,n} = \frac{C_k C_{gs,n}}{(C_k + C_{gs,n})}$ and pMOS devices $M_{4,5}$, $C_{k,p} = \frac{C_k C_{gs,p}}{(C_k + C_{gs,p})}$ and other layout

Fig. 2: Schematic of the CMOS cross-coupled oscillator based super-regenerative amplifier

parasitic capacitances. The quality factor of the resonator is degraded by the antenna impedance represented by the differential load $R_L = 100 \Omega$ and the coupling capacitor $C_C = 390 \text{ fF}$, to an effective $Q_{\text{eff}} \approx 3.6$ at $f_{\text{osc}} = 28.2 \text{ GHz}$. The corresponding effective parallel resistance of the resonator is $R_R = \omega_{\text{osc}} L_R Q_{\text{eff}} \approx 95 \Omega$. The two parallel branches of thin oxide nMOS accumulator mode varactors having a combined capacitance range of $C_{\text{min}} = 7.7 \text{ fF}$ to $C_{\text{max}} = 44.1 \text{ fF}$ are used for differential frequency tuning. The capacitance $C_k = 48.3 \text{ fF}$ is designed to limit the voltage swing at the gate of the transistors, and have a peak voltage swing higher than V_{CM} across the inductor. In steady state, the negative resistance required for sustained oscillations is obtained from the transconductance $g_{m,n}$ and $g_{m,p}$ of the nMOS pair and pMOS pair respectively as, $R_A \approx \frac{-2}{g_{m,n} + g_{m,p}}$. Where R_A is determined from the resonator effective resistance as $R_A \approx -\frac{R_R}{3} \approx -47 \Omega$, and corresponding transconductance is calculated as $g_{m,n} = g_{m,p} = 21 \text{ mS}$. The bias current 9.6 mA corresponding to this transconductance is set by the current mirrors transistors M_7 and M_8 . This current also sets the peak-to-peak output voltage swing of 1.1 V , resulting in an output power $P_{\text{dBm,out}} = 2 \text{ dBm}$. The gate of switching transistor M_1 is over-driven by the quench signal V_Q , which swings from V_{SS} to V_{DD} , and the gate of switching transistor M_6 is over-driven by the $V_{Q,C}$, generated from V_Q using a CMOS inverter. This lets M_1 and M_6 operate between cut-off and triode regions to quench the oscillations on and off. A periodic V_Q can thus vary the transconductance across the resonator from zero to 21 mS and back to cause superregeneration of an input signal present across the resonator.

Fig. 3: Illustration of the measurement setup around the chip micrograph of the SRA measuring $820 \mu\text{m} \times 820 \mu\text{m}$ including pads.

The circuit is implemented in the 45 nm SOI technology from GLOBALFOUNDRIES using minimum length floating body transistors. Layout of transistor interconnects are done with double-gate contacts similar to that illustrated in [8]. Common centroid layout is done for transistors $M_{2,3}$ and $M_{4,5}$ to reduce the sensitivity to threshold voltage variations. DC biasing interconnects are implemented using custom-designed zero-ohm transmission lines based on design principles discussed in [9].

III. CHARACTERIZATION

The fabricated integrated circuit shown in Fig. 3, is characterized by micro-probing. Parameters including f_{osc} , the output power $P_{\text{dBm,out}}$, input sensitivity $P_{\text{dBm,min}}$ and bandwidth BW are characterized using the test setup consisting of a Rohde & Schwarz FSU spectrum analyzer, Keysight 8257D RF signal source, and an arbitrary waveform generator for quench waveform generation as shown in Fig. 3. With the quench signal V_Q is kept high, the circuit operates in the free-running oscillator mode, and f_{osc} is measured by varying the varactor voltages $V_{\text{var,p}}$ and $V_{\text{var,n}}$. The measured frequency variation from 28.07 GHz to 29.35 GHz is shown in Fig. 4(a).

In order to characterize the operation of the circuit as a SRA, the oscillator has to be quenched ON and OFF. Since the time domain measurements of regenerative sampling is not practical at the oscillation frequency, characterization is done using the spectral measurement procedure described in [5]. When V_Q is applied as a periodic pulse, and when input is present outside the regenerative sampling frequency range, a *sinc* spectrum can be measured as shown in the blue trace with triangle markers in Fig. 4(c). When V_Q is applied as a periodic pulse, and an input signal is present within the regenerative sampling frequency range, the characteristic delta function peaks are observed superimposed on the *sinc* spectrum as shown in the black trace with dotted markers in Fig. 4(c). Frequency response measurements are done for different input signal power levels $P_{\text{dBm,in}}$ as shown in Fig. 4(b) to determine the regenerative sampling frequency range and bandwidth (BW), which increases with increased input power levels. In

Fig. 4: (a) Simulated and measured differential tuning range of the SRA in free-running mode, showing frequency tuning from 28.07 GHz to 29.36 GHz. (b) Measured peak output power spectral density vs. input power, with marking of linear mode to logarithmic mode transition points for sinusoidal and pulsed quenching. (c) Measured power spectral density with $P_{\text{dBm,min}} = -85$ dBm at $f_{\text{osc}} = 28.24$ GHz. (d) Measured normalized frequency response for various input power levels, showing an increase in bandwidth with increase in input power.

Fig. 4(b), the peak power spectral density measurements with a pulsed V_Q are compared with measurements with a sinusoidal V_Q . The delta function peaks indicating regenerative sampling starts to appear from $P_{\text{dBm,in}} = -85$ dBm, and the output power $P_{\text{dBm,out}}$ increases linearly. With pulsed quenching, from $P_{\text{dBm,i,N}} = -64.9$ dBm, the output power starts to saturate, as the SRA enters the logarithmic mode. With sinusoidal quenching, this power is measured to be $P_{\text{dBm,i,N}} = -66.3$ dBm. The circuit draws a current of 9.6 mA from 1.1 V power supply, consuming 10.6 mW when operating as a free-running oscillator, and 5.3 mW when quenched with a periodic pulse with 50% duty cycle. Measurements are done till a maximum pulse repetitive frequency of 22 MHz.

TABLE I: Comparison with State-of-The-Art FMCW Radar Active Reflectors

Ref.	[5]	[6]	[7]	[10]	This
f_{osc} (GHz)	34.5	6.8	5.8	77	28.2
$P_{\text{dBm,min}}$ (dBm)	-80	-65	-64	NA	-85
$P_{\text{dBm,i,N}}$ (dBm)	-67	NA	NA	NA	-63.6
$P_{\text{dBm,out}}$ (dBm)	5.6	-4.7	1	-14	1.1
BW (GHz)	0.5	2.3	0.15	5	0.25
P_{DC} (mW)	122	130	54	18	10.6
Topology	SRA	SRA	Pulsed	BPSK mod.	SRA
Tech.	250 nm BiCMOS	250 nm BiCMOS	180 nm CMOS	45 nm SOI	45 nm SOI

Table I compares various state-of-the-art active reflectors for FMCW radars against the implemented circuit. Implementation complexity is high in [5], which uses an LNA and multiple PA stages, and in [10], where a combination of LNA, a BPSK modulator and a VGA are used. [6] and [7] are similar to this work, but operates at a lower frequency, and has high DC power consumption.

IV. CONCLUSION

The design, layout, and characterization results of a super-regenerative amplifier, implemented in 45 nm SOI technology, targeting FMCW radar reflector applications is presented in this paper. The SRA has an operating frequency range of 28.07 GHz to 29.35 GHz, detects input signals as low as -85 dBm, and delivers 1.1 dBm output power into a 100 Ω differential load consuming a low DC power of 10.6 mW. The SRA also has the best combined sensitivity and output power for an FMCW radar reflector implementation in CMOS.

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