Ka-Band TDD Front-End with Gate Shunt Switched Cascode LNA and Three-Stack PA on 22nm FDSOI CMOS Technology

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Abstract— TDD Ka-band front-end with integrated switch on 22nm FDSOI CMOS technology is implemented for 5G NR at 24-28 GHz bands. Shunt switch technique reduces front-end performance only by 2 dB at 24 GHz compared to stand-alone reference amplifiers. Output power of TX with stacked PA is 13.6 dBm with 15 dB of peak gain, and RX front-end has 5dB noise figure at 24 GHz, both measured at the antenna port. Maximum average channel power at 28 GHz was 4.8 dBm with 100 MHz 64-QAM OFDM signal within 5G ACPR and EVM specifications. The PA and LNA amplifiers dissipate 183 mW and 4.6 mW from 2.8V and 0.8V supplies, respectively, occupying only 0.19mm².

Keywords— CMOS, LNA, mmWave, PA, SOI, TDD.

I. INTRODUCTION

Commercialization of 5th generation communications (3GPP 5G NR) at low end of millimeter wave spectrum (mmW) requires highly integrated, area efficient broadband phased arrays. Time division duplex (TDD) antenna front-ends (FE) using modern CMOS processes are susceptible to low breakdown voltages. Specific attention should be paid to low loss TX-RX switch that is a key element in the front-end. 22nm Fully Depleted Silicon-on-Insulator (FDSOI) technology is suitable solution for mmW integration with possibility to combine digital processing with high performance active and passive RF circuitry [1]. In addition, stacked PA structures favored in SOI based technologies allow higher power via higher supply voltages, but on the other hand can easily stress front-end switch beyond acceptable limits [2],[3].

High array gain to achieve decent link budget requires a large number of parallel antenna front-ends both in base station and in mobile devices. Therefore, a major portion of power of a wideband transceiver system is dissipated in radio front-end. In TDD systems, low power consumption and noise figure in the receiver are as important as decent efficiency and output power in the transmitter, especially in mobiles when there is more traffic in downlink direction. Therefore, TX-RX switching mechanism should have the lowest possible loss in both modes minimally loading the other operation mode. At mmW frequencies, such switch is not feasible to implement with a single switching transistor due to excessive parasitics and limited voltage handling capabilities of modern small gate length devices. In previous work, capacitive parasitics have been resonated out with inductors that add area penalty [4]. Alternative way is to use quarter-wave transformers to isolate

PA and LNA. However, those are even larger structures and are difficult to tune [5]. Common matching techniques have also been reported, however these tend to have complex and time consuming iterative process from closed form design equations to practical implementation [6],[7]. Nevertheless, a straight forward solution to implement a front-end without bulky and lossy switch structures would improve efficiency and reduce cost and design time significantly.

This work demonstrates a simple yet effective technique to combine LNA and stacked PA together using FDSOI technology by taking an advantage of a large inductance of a source degenerated LNA input matching network and adding a shunt switch to ground at LNA input to make the LNA appear as a high impedance inductive load for the PA. In addition to FE, Separate standalone PA and LNA test structures were included on the same die to evaluate the effective performance degradation of the front-end implementation at 24-28 GHz.

II. SCHEMATIC

A. 3-Stack Power Amplifier

The schematic of the front-end is presented on Fig. 1. The PA is a 3-stack amplifier that allows higher supply voltages up to 2.8V from the nominal 0.8V. The PA is matched with transformers. In the input, the secondary winding of XF1 loaded with C1 compensates the PA input capacitance and effectively changes the transformer ratio, so that conjugate matching is achieved. The output is matched in similar manner to Γ_{opt} . The primary side of XF2 is loaded with C4 so that the load seen by the PA is down-converted from secondary side impedance. The PA core is inter-stage matched with shunt capacitors C2 and C3 at the gates of M1 and M2. 2.8V Supply voltage was isolated from the RF using a 1 nH choke. Transistor core is split into four cells each consisting of five 15 μ m parallel transistors totaling to width of 300 μ m. Each gate bias of the stack (V_{g1} , V_{g2} , V_{g3}) is controlled via series resistor from off-chip PCB board. Additionally back-gate biases (V_{bg1} , V_{bg2} , V_{bg3}) were controlled in a similar manner.

B. Low Noise Amplifier

The LNA is a source degenerated cascode, which was designed with minimum noise figure in mind. Circuit design procedure was as follows. First, the input matching network

Fig. 1. Front-end schematic.

was designed with some starting values for transistor width and source inductor. Matching is mainly inductive, but a small shunt capacitance was required for optimum noise match. This was implemented together with parasitic capacitances of input stage transistor and with shunt switch transistor. Then the load resonator was designed to have LNA gain peak at 28 GHz, and finally the output was matched with an LC-network to 50Ω including a DC-block capacitor. The transistors are biased close to minimum noise current density of $0.15\text{ mA}/\mu\text{m}$ or 4.5 mA with $30\mu\text{m}$ devices. Stability is ensured with small load to source inductance ratio at a cost of gain.

As mentioned above, all amplifier transistors have backgate connection to study the possible tuning enhancements. Back-gate is simply an additional connection to transistor that allows tuning of the threshold voltage of the transistor with roughly $80\text{ mV}/\text{V}$ sensitivity on this technology [8]. In addition, all capacitors are vertical natural capacitors implemented with lower level metals.

Switch (M6) in the design is controlled to conduct (gate voltage at VDD) in TX mode to protect the LNA gate from large PA output signal swings. The technique is similar to 28nm bulk CMOS implementation in [9] in which differential PA is used. In RX mode the switch is nonconducting and is a part of the matching capacitance of the LNA. Adjusting the VDDs and control signals is done off-chip. In RX mode, the PA VDD is off to minimize any noise that PA generates. Simply switching the biases to 0V would break voltage balance of the PA stack resulting in breakdown of gate oxides.

C. Manufactured Circuits

Chip micrographs are presented in Fig. 2. Changes between the reference amplifiers and front-end are minimal. In the layout, the LNA input matching inductor L2 had to be modified to connect to a common antenna port. The inductance was increased from 660 pH to 710 pH for optimum performance. Additionally, a DC-block capacitor (C6 in schematic) was added to PA matching network to prevent leakage from LNA bias to ground.

Fig. 2. Front-end, reference LNA and reference PA microphotographs.

III. MEASUREMENTS

S-parameters, linearity and noise figure were measured with Keysight PNA-X microwave network analyzer N5247A and a UXA signal analyzer N9040B with noise figure option, noise source 346CK01 and U7228F pre-amplifier. Test chip was probed with Cascade Microtech GSG and GSGSG probes.

A. RX

S-parameters of RX front-end and reference LNA are presented in Fig. 3a. Bias was tuned for maximum gain using 5.8 mA of quiescent current and then back-gate voltages ($V_{bg1} = -0.4\text{V}$ & $V_{bg2} = 0.9\text{V}$) were optimized while maintaining the same bias current in order to boost the gain even further.

Off-state PA shifts the center frequency of the LNA from 27.8 GHz to 26.4 GHz that could be tuned back with slight modifications. Peak gain drop of 2 dB is mainly caused by signal leaking to PA. Noise figure degraded from 3 dB to 5 dB at 24 GHz . Fig. 3b shows that optimum back-gate bias setup not only increased the gain, but also improved the compression point. This did not have an impact on the noise

Fig. 3. Measured reference LNA and front-end RX S-parameters and noise figure (a), and gain and compression point with gain optimized backgate biases (b).

figure. Back-bias voltages improve the voltage balance over cascode transistors from 38%/62% to 51%/49% in simulations giving more headroom for larger signal swings. Comparing the reference LNA and front-end RX performance, the gain and noise figure degraded 2-5 dB over 24-28 GHz frequency range. Above 26 GHz, part of the receive signal sinks to PA output matching network which resonates around 30 GHz resulting in increase in noise figure.

B. TX

Front-end integration impact on TX performance is limited to additional switch loss which is shown in 1-tone measurements in Fig. 4. Difference in output power is below 2 dB from 24 GHz to 28 GHz indicating decent de-Q and bandwidth extension due to the switch. Wide TX bandwidth indicates a possibility to tune the TX matching network to a higher frequency improving noise figure degradation without additional TX penalty. Due to the switch loss, peak PAE decreased from 23% to 10% showing a good efficiency among

Fig. 4. Measured 1-tone compression, AM-PM and PAE of TX FE and reference PA at 28 GHz (a), and P_{sat} and TX loss over frequency (b).

Ka-band CMOS front-ends. The non-linear load, M6, has impact on compression impacting AM/PM distortion at lower output power levels that can be compensated with proper linearization.

C. Modulated Measurements

TX performance was tested with 100 MHz wide cyclic prefix - orthogonal frequency division multiplexing (CP-OFDM) 64-QAM modulated signal following the 3GPP/NR standard for FR2. The used waveform has peak-to-average-power-ratio (PAPR) of 10.9 dB due to the OFDM. Signal was generated with Keysight M8190A Arbitrary waveform generator and upconverted to 28 GHz by Keysight E8267E signal generator. The output was measured

Fig. 5. Measured constellations without (a) and with DPD (b).

Fig. 6. Measured output spectrums with (red) and without DPD (blue) with 4.8dBm output power.

Fig. 7. Measured output channel power, ACPR and EVM as function of output power with DPD and 5G specifications from [12] for 100 MHz 64-QAM signal.

Table 1. Comparison of mmWave TDD front-ends.

Reference	This work	[9]	[4]	[5]	[6]	[10]	[11]	[7]
Switch type	RX shunt gate		SPDT	1/4λ TL	Common match			
Freq [GHz]	24-28	25-30.5	30-40	27-29	57-65	27-40	60-67	25-30
RX gain [dB]	7	34*	17	30*	21.5	16.1	17	11
RX P1dB [dBm]	-9.1	-	-17	-22.5*	-	-15.7	-25	-7.1
RX NF [dB]	5	3.8*	8.4 (sim)	6	6.7	6.2	6.8	3.5
Pdiss RX [mW]	4.6	42*	48	103.1*	39.6	17.6	<28.8	28
TX gain [dB]	15	44*	14	15	24.5	28.5	24	12
TX P1dB [dBm]	7.4	12*	20.5	13.5	5	14.1	10	22
Pdiss TX [mW]	183	90*	352	143.8*	71	96.2	<63.5	230
Psat [dBm]	13.6	14	22.5	16	8.4	15.8	10	23.6
PAE [%]	9.6	20	7	21	8.7	20	-	28
Active area [mm ²]	0.19	1.16*	7*	4	0.22	0.35	0.35	0.275
Process	22nm SOI CMOS	28nm CMOS	130nm SiGe	65nm CMOS	28nm CMOS	45nm SOI CMOS		

*complete TX/RX chain

with Keysight N9040B UXA. To meet the 3GPP/NR FR2 specifications of 8% EVM and 28 dBc ACPR, digital predistortion (DPD) was applied to the signal [12]. Output constellation diagrams and spectrums with and without DPD are shown in Fig. 5 and Fig. 6 respectively. Maximum channel power is 4.8 dBm indicating a realistic 9 dB backoff for the used waveform which mean that the waveform peaks are already almost 2 dB in saturation. ACPR and EVM characteristics over measured output power range are shown in Fig. 7. EVM starts to deteriorate when the back-off is over 11dB, close to the waveform PAPR.

IV. CONCLUSION

The front-end is compared to reported state-of-the-art front-ends with various switch topologies in Table 1. This is the first front-end implemented on 22nm FDSOI technology achieving lowest area and RX power dissipation, while providing competitive output power, efficiency and receive noise figure. Measurements with real 5G NR test signals show capability to support even 64-QAM OFDM signals with 9 dB backoff. Simple design minimizes workload in front-end co-design. At 24 GHz, RX and TX performance is degraded only by 2 dB which is only possible to achieve using a switch topology with decent isolation. Output power and receive noise figure can be further improved by more careful PA load impedance tuning and adding more transistors to PA stack.

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