Co-Design of 60GHz Wideband Front-End IC with On-Chip Tx/Rx Switch Based on Passive Macro-Modeling

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Abstract — **Co-design of 60GHz wideband front-end IC with on-chip Tx/Rx switch in 65nm CMOS is presented. Passive macro-modeling (pmm) is utilized to convert S-parameter files from passive component EM simulations to state-space models in circuit netlist format which could be used in commercial SPICE simulator for various analyses without convergence issues. The co-design of on-chip switch and LNA/PA could achieve wideband matching and reduce the effects of insertion loss of on-chip Tx/Rx switch. Combining with gain boosting technique in LNA design and lumped-component based design methodology, the implemented 60GHz front-end IC with on-chip Tx/Rx switch achieves 3dB gain bandwidth of 12GHz with maximum gain 17.8dB and minimum NF 5.6dB in Rx mode and 3dB gain bandwidth of 10GHz with saturated output power 5.6dBm in Tx mode, and only consumes 1.0mmx1.2mm die area (including pads).**

Index Terms — **Mm-wave, low noise amplifier (LNA), power amplifier (PA), single-pole-double-throw T/R switch, Passive macro-modeling (pmm)**

I. Introduction

Along with the rapid technology scaling, the developments of CMOS millimeter-wave (mm-wave) integrated circuits and systems have attracted a lot of attentions among the world [1]. In mm-wave frequency band, the foundry usually couldn't provide the accurate electrical models of various passive components which are widely used in mm-wave ICs, and EM simulations are utilized in common to extract the electrical characteristics of these passive components with S-parameter description format. Although some EDA simulation tools support the electrical models described in S-parameters, the convergence is a big issue, especially during transient and linearity simulations.

Compact modeling is an effective way to solve the above issue, but wideband mm-wave passive component modeling in itself is a very challenging task and need a lot of efforts, especially for IC designers.

In this paper, we utilized pmm (Passive Macro-Modeling) Matlab toolbox developed by us to convert industrial-standard touchstone format S-parameter files from passive component EM simulations to state-space models in circuit netlist format which could be used in commercial SPICE simulator for various analyses. Then these state-space models are used to develop a 60GHz front-end IC with on-chip Tx/Rx switch for low-cost short-range high-speed wireless communication applications.

In low-cost short-range 60GHz wireless transceivers, off-chip SPDT switch is unacceptable due to the assemble difficulty and high cost. In [1], the transceiver uses two off-chip antennas (one for Rx and another one for Tx), whose size is much larger than the chip's size.

Although some literatures discuss the implementations of mm-wave on-chip SPDT switches [2], there are few reports to integrate Tx/Rx switch with other mm-wave blocks, especially in CMOS technology. In [3], a CMOS transceiver chipset with on-chip transformer-based Tx/Rx switch is presented, but the measured minimum DSB NF of Rx is 14dB.

In this paper, we present a 60GHz wideband front-end IC with on-chip Tx/Rx switch in 65nm CMOS. The co-design of on-chip switch and LNA/PA could achieve wideband matching and reduce the effects of insertion loss of on-chip Tx/Rx switch as much as possible. Combining with gain boosting technique in LNA design and lumped-component based design methodology, the implemented 60GHz front-end IC with on-chip Tx/Rx switch achieves high performance and only consumes 1.0mmx1.2mm die area (including pads).

II. Passive Macro-Modeling (pmm)

Pmm is a Matlab toolbox developed by us [4] for passive macro-modeling from frequency-domain (measured or EM-simulated) tabulated data, such as S-parameter data. It takes industrial-standard touchstone format files as input, and generate state-space model in circuit netlist format which can be used in commercial SPICE simulator for doing various analyses. The state-space model is described in the following equation:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

The frequency domain transfer function of the above state-space model is:

$$H(s) = C(sI - A)^{-1}B + D$$

The transfer function of the state-space model should match the input tabulated data from EM simulator, i.e. HFSS. Thus finding the proper state-space model becomes minimizing the following error.

$$Err = \sum_{k=1}^{n_s}\sum_{p=1}^{N}\sum_{q=1}^{N}\left|H_{pq}(s_k) - S_{pq}(s_k)\right|$$

Where $S_{pq}(s_k)$ is the S_{pq} parameter at frequency s_k. To avoid causing convergence issue, the passivity of the model should be ensured. Such issues have been tackled within pmm toolbox by using new passivity enforcement technique.

The procedure of utilizing pmm is described as follows. First, full-wave EM simulation tool (such as HFSS) is utilized to extract the electrical characteristics of mm-wave passive components with S-parameter description format. Then pmm converts the resulted S-parameter files to state-space models in circuit netlist format which could be used in commercial SPICE simulator for various analyses.

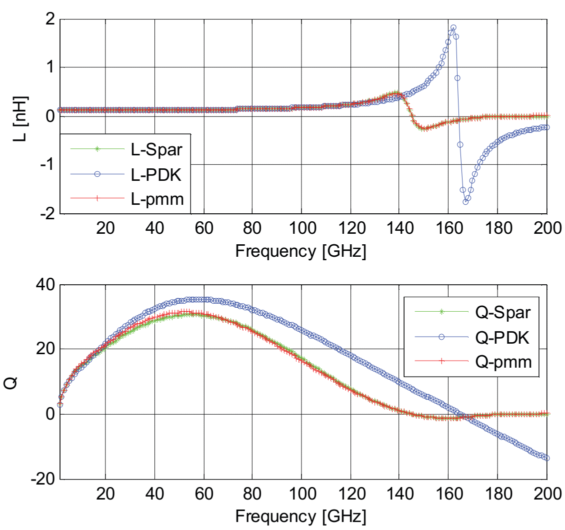

Fig. 1. The simulated L and Q for one inductor with PDK model, S-parameter tabulated data from HFSS and sub-circuit netlist from pmm, respectively.

Fig.1 shows the simulated inductance (L) and quality factor (Q) for one inductor using the top metal layer with 3.4um thickness, with PDK model provided by the foundry (only limited to <30GHz frequency range for accuracy), S-parameter tabulated data from HFSS and sub-circuit netlist from pmm, respectively. The figure shows good agreements among them.

III. 60GHz Wideband Front-End IC with On-Chip Tx/Rx Switch

A. Block diagram

Fig. 2 shows the block diagram of the presented front-end IC, it consists of three blocks: a low noise amplifier (LNA), a power amplifier (PA) and a single-pole-double-throw (SPDT) Tx/Rx switch.

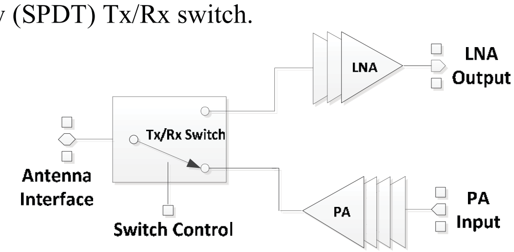

Fig. 2. The block diagram of the presented 60GHz front-end IC with on-chip Tx/Rx switch.

The input of LNA and the output of PA are connected to the SPDT Tx/Rx switch. The front-end IC can be set to Tx mode or Rx mode by driving the “Switch Control” signal to low or high. The Switch Control signal also controls the operation modes of LNA and PA by setting the bias voltage of LNA (PA) to 0 for power-down or normal bias voltage for power-on. So in Tx or Rx mode, LNA or PA is powered down, which can further increase the isolation between LNA and PA. Since the Tx/Rx switch resides before the LNA and after the PA, its insertion loss should be minimized in order not to degrade the sensitivity of the receiver and the transmitter output power.

B. Co-design of front-end blocks with on-chip Tx/Rx Switch for Wide Bandwidth

Fig.3(a) gives out the schematic of on-chip Tx/Rx switch with its interfaces with LNA and PA blocks. Multi-stage LC networks are utilized to achieve wide match bandwidth by co-design and co-optimization of Tx/Rx switch with PA/LNA. Fig.3(b) and Fig.3(c) give out the simplified match schematics when the front-end works in Rx mode and Tx mode, respectively. Here, Ceq is the off-state capacitance of the shunt switch transistor and Leq is the equivalent inductance looking into the secondary spiral of the transformer at the last stage output of PA. By co-designing and co-optimizing the size of the shunt switch transistors and the passive component values, wide matching bandwidth could be achieved while keeping a low insertion loss, as verified by the measured results. Compared with the traditional independent design of Tx/Rx switch and front-end blocks, the co-design obviously shows superior performance.

On-chip Tx/Rx switch used here is a shunt-shunt based single-pole-double-throw switch with high isolation. TL1 is only for signal routing. The capacitance of the G-S-G pad is taken into account by EM simulation. R5-R7 provides high resistance substrate for the transistors M1-M4 and lower down the insertion loss.

PA is a four-stage cascaded amplifier. The first and second stages use single-ended CS topology to provide high gain with low power consumption, while the third and fourth stages are transformer-based differential CS topology to provide sufficient output power. The bias of the transistors is connected to the center tap of the secondary spiral of the transformers.

LNA is composed of three cascaded amplifiers, and each of them contains a cascode structure to provide high input-output isolation for good stability. The bias current densities of the amplifying transistors are all set to 0.15mA/um to achieve the optimum noise performance [3]. To provide sufficient gain, inductors are inserted between the CS and CG stages to resonate out the parasitic capacitors so that the gain could be boosting.

In our design, lumped inductors and transformers are widely used to save die area, while the micro-strip transmission-lines are mainly used for signal routing between devices.

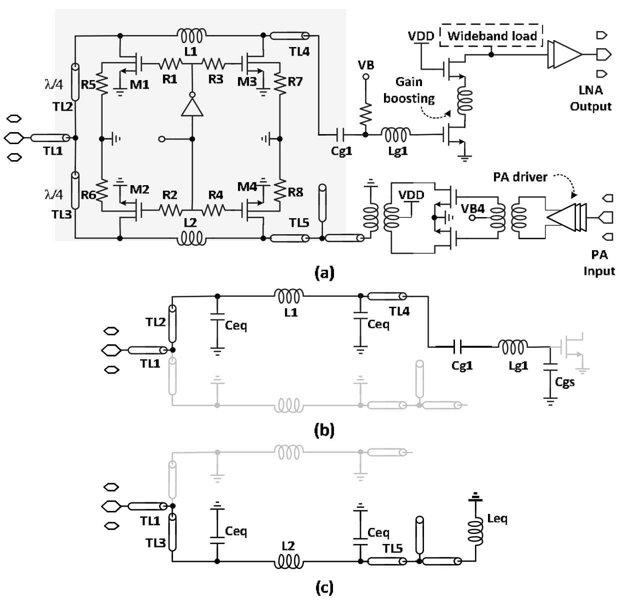

Fig. 3(a) Schematic of on-chip Tx/Rx switch with its interfaces with LNA and PA. (b) Simplified matching schematic in Rx mode. (c) Simplified matching schematic in Tx mode.

IV. Measured Results

The 60GHz frond-end IC with on-chip Tx/Rx switch has been implemented in 65nm CMOS with 9 metal layers. Fig. 4 shows the microphotograph of the chip. The die area is only 1.0mm x 1.2mm, including pads.

The front-end IC chip was assembled on a PCB-substrate with DC-bias pads bonded to the PCB. Accurate S-parameter measurements were performed up to 67GHz using the RF probes and Agilent network analyzer. Fig.5 shows the measured S-parameters of Tx channel in Tx mode. The small signal gain (S21) of PA cascaded with Tx/Rx switch is 20.5dB at 60GHz with a peak of 21.5dB at 57GHz. It could be seen that 10GHz -3dB gain bandwidth is achieved. Both the input return loss (S11) and the output return loss (S22) are below -10dB over 56-66GHz, showing good input and output matching.

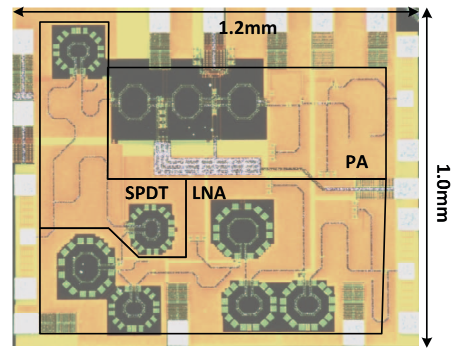

Fig. 4. Die microphotograph of the presented front-end IC.

Fig.6 shows the measured S parameters of Rx channel in Rx mode. The small signal gain (S21) is higher than 15dB over -3dB bandwidth 54-66GHz with a peak of 17.8dB at 60GHz. Both S11 and S22 are below -10 dB over 56-66GHz, also showing good input and output impedance matching.

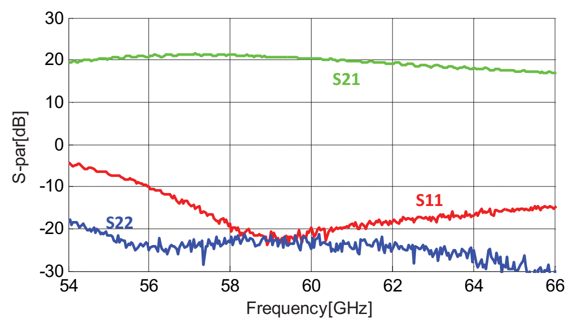

Fig. 5. Measured S parameters of TX channel (Switch & PA).

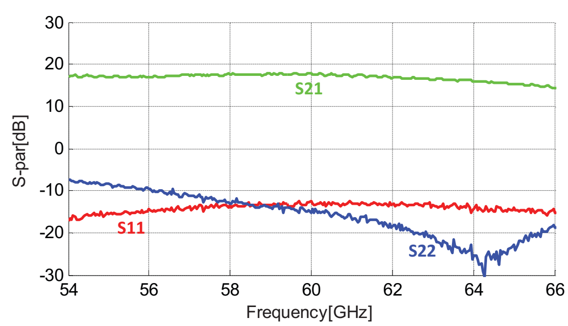

Fig. 6. Measured S parameters of RX channel (Switch & LNA).

67GHz signal generator and power meter were used to measure the output power characteristic of the chip in Tx mode. The measured output power versus input power is shown in Fig.7. The saturated output power at the antenna interface is 5.6dBm at 57GHz and 5.1dBm at 60GHz. The

simulation shows that the integrated on-chip Tx/Rx switch reduces the saturated output power by 2.1dB, but it could reduce the cost by a lot.

The noise measurement of the chip in Rx mode is carried out by including a linear mixer to down-convert the noise information to IF. The noise contributed by the linear mixer, the intrinsic noise of the spectrum analyzer, the loss of the cables and the probes is calibrated. Due to the equipment limits, only 62-67GHz noise data was got. The measured NF of Rx channel (Tx/Rx switch cascaded with LNA) in Rx mode is shown in Fig.8. A minimum NF of 5.6dB is achieved at 62.6GHz. The simulation shows that the integrated on-chip Tx/Rx switch increases NF by 2.0dB.

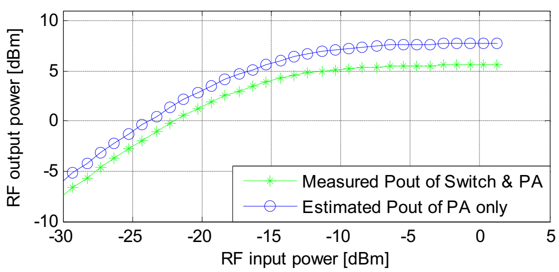

Fig. 7. Measured output power of Tx channel.

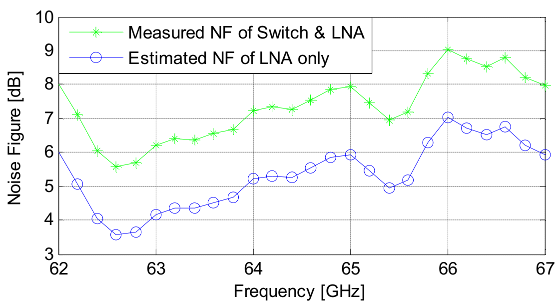

Fig. 8. Measured Noise Figure of Rx channel.

The chip consumes 96.2mA DC current in Tx mode and 13.2mA current in Rx mode. Table I summarizes the performance of the presented 60GHz front-end and makes a comparison with the state-of-the-arts.

V. Conclusion

In this paper, the co-design of 60GHz wideband front-end IC with on-chip Tx/Rx switch in 65nm CMOS is presented. Passive macro-modeling (pmm) is utilized to convert S-parameter files from passive component EM simulations to state-space models in circuit netlist format which could be used in commercial SPICE simulator for various analyses without convergence issues. The co-design of on-chip switch and LNA/PA could achieve wideband matching and reduce the effects of insertion loss of on-chip Tx/Rx switch. Combining with gain boosting technique in LNA design and lumped-component based design methodology, the implemented 60GHz front-end IC with on-chip Tx/Rx switch achieves high performance and only consumes 1.0mmx1.2mm die area (including pads).

TABLE I PERFORMANCE SUMMARY AND COMPARISON WITH THE-STATE-OF-ARTS

	Our work Switch & LNA	[3] Receiver & Switch	[5] LNA only	[6] LNA only
Gain	17.8 dB (Peak)	35dB	14.7dB	21dB
3dB Gain BW	12GHz	N.A.	7 GHz	4.5 GHz
NF	5.6dB (Minimum)	14dB (DSB)	6dB	8.3dB
S11/S22	<-10dB (56-66GHz)	N.A.	N.A.	N.A.
P_{DC}	13.2mW	233mW	64.8 mW	15.1 mW

	Our work Switch & PA	[3] Transmitter & Switch	[7] PA only,45nm CMOS, 94GHz
Gain	21.5dB(Peak)	15dB	18.5dB
3dB Gain BW	10GHz	N.A.	14 GHz
Saturated Power	5.6dBm	6dBm	7.6dBm
S11/S22	<-10dB (56-66GHz)	N.A.	N.A.
P_{DC}	96.2mW	160mW	120mW

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