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ADS-CST Co-Simulation and Performance Evaluation of MMIC Power Amplifier for Millimeter-Wave Automotive Radar Applications

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Abstract

This paper shows a detailed co-simulation guided design and analysis of a monolithic microwave integrated circuit (MMIC) power amplifier (PA) to be used in millimeter-wave (mmWave) automotive radar with voltage-controlled oscillator (VCO) operating at 76-81GHz band. The suggested technique is comprised of Keysight Advanced Design System (ADS) (nonlinear, circuit-level synthesis) and CST Microwave Studio (full-wave, 3D, electromagnetic (EM) simulations) to help it perform package-aware as well as prove to be layout-accurate. The MMIC PA is realized in 0.15 µm GaAs pHEMT technology and it has a two-stage common-source topology with a high-gain, power-added efficiency (PAE) optimisation. The early-stage design in ADS incorporates load-pull simulation and harmonic balance analysis of the design combined with simulation in CST to model the EM effects due to layout parasitics, ground discontinuities and interconnects. Co-simulation output performance shows small-signal gain peaking at 21 dB at 77 GHz, having a saturated output of +18.2 dBm as well as a peak PAE of 32% all with equally good input and output matching (S11 < -10 dB). The amplifier has realistic substrate and bias conditions and remains thermally stable and electromagnetically sound. The co-design method minimizes the differences between schematic and fabricated performance which facilitates reduced prototyping time and lead time and the robustness of the design. This research emphasizes that EM-circuit co-simulation plays a very crucial role in mmWave MMIC design and determines a proven approach to the design of high-performance compact power amplifiers in new generation vehicles radar and 6G communications applications.

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Introduction

Radar systems used in automobiles consist of a frequency range of 76-81 GHz and are critical to advanced driver-assistance systems (ADAS) and autonomous driving features. Such systems are particularly sensitive to the quality of high-performance millimeter-wave (mmWave) components and in particular the power amplifier (PA) that must achieve high gain and output power at low cost, giving it extremely demanding requirements to size, efficiency and thermal reliability.[1, 2] The new interest development using GaAs and GaN technologies has been the development of monolithic microwave integrated circuit (MMIC) PAs with high frequency, wideband and compact integration which has made them useful in vehicular radar applications. Circuit-level-only PA design tools, such as harmonic balance and load-pull in ADS fail to consider layout parasitics and the effects of packaging discontinuities, EM coupling, and the like. These contribute discrepancies between simulation and measured performance to cause degradation in the performance of prototypes such as return loss, power-added efficiency (PAE) and gain in fabricated prototypes.[4]

To overcome it, the present work introduces a hybrid co-simulation approach that combines Keysight Advanced Design System (ADS) which is used as a nonlinear circuit modeling tool with the CST Microwave Studio used as full-wave 3D electromagnetic analyzer. Such a unified scheme results in layout-aware optimization, to support higher accuracy of prediction along with faster convergence during optimization to fabrication-ready MMIC design. There is a lack of detailed co-simulation processes of mmWave MMIC PAs, which are in detail tailored specifically to the emerging automotive radar band at 76-81 GHz and have EM validation.[11] The paper bridges this gap and offers a solid design paradigm to next-generation radar, as well as 6G sensing systems.

Related Work

Power-efficient and miniaturized mmWave power amplifiers (PAs) are a prominent example of the technological advancements achieved in the past decades, highly driven by the current trends of high-frequency applications in the industry, including 5G, 6G, and automotive radar. Enhancement of gain, linearity, power-added efficiency (PAE) and bandwidth and minimization of footprint and thermo challenge of amplifiers based on MMIC have been the key aspects of researcher interest.[5, 6] Keysight ADS or Cadence SpectreRF circuit simulators are frequently used in a traditional PA design strategy and offer robust harmonic balance and load-pull non-linearities but do not encompass layout-sensitive phenomena such as electromagnetic (EM) coupling, proximity effects between metal and metal, and substrate radiation. These parasitics may be able to have a large effect on practical performance, especially at mmWave frequencies above 60 GHz.[7] In order to circumvent such drawbacks, various efforts to combine EM solvers like HFSS or CST and circuit-level simulators as part of co-simulation have been incorporated. These hybrid methods enhance post-layout accuracy consideration of microstrip discontinuities, packaging interfaces, and grounding methods.[8, 9] Nevertheless, there have been few reports directed towards the MMIC PA co-design that specifically targets automotive radar with extreme requirements that include not only operating in the 7681 GHz band but also high ruggedness and temperature range operation as well as a PAE in excess of 20%.[10]

In addition, most of the reported works may not have full consideration to 3D packaging and thus there is an underestimation of mismatch loss and power degradation following integration. This means that a strongly focused co-simulation approach that takes into account both ADS nonlinear circuit design and CST 3D EM validation is a key enabler to providing packaging-aware, production ready MMIC PA solutions that are suited to radar systems in autonomous vehicles.

Methodology

Design Flow Overview

In order to meet the design requirements of circuit level efficiency and electromagnetic integrity of a millimeter-wave power amplifier (PA) design process, we will use a co-simulation approach within and between the Keysight Advanced Design System (ADS) and CST Microwave Studio (MWS).[12] This method sits between the design approach rooted in nonlinear transistor-level modeling and full-wave electromagnetic (EM) simulations, and it will allow prediction of the device behavior in the lab. Design flow has been described in four major steps:

1. Initial Circuit Design in ADS:

It starts with the schematic level design through the ADS which has a comprehensive support of nonlinear simulations and the harmonic balance analysis:

- Transistor Model Selection: One of the commercial GaAs pHEMT active devices is selected to use at its high-frequency and power handling capabilities that will satisfy in the 7681 GHz operation.[15]
- Bias and Matching Network Design: The source, gate and drain bias networks are designed and conjugate matching networks (with maximum power gain) are designed.
- Harmonic Balance Analysis: Non-linear simulation is done with an aim to investigate the gain compression and power efficiency added (PAE) as well as the saturation performance of the frequency range desired.

2. Layout Extraction and EM Export:

When validated:

- Its layout is created with ADS Layout Editor, adding interconnects, transmission lines, via and ground pad with the use of the foundry rules.
- The layout that has been done is converted to DXF/GDSII and imported to CST MWS where the field-level simulation is done. This guarantees the retention of layer definitions and geometries (physical) of 3D modeling.

3. 3D EM Simulation in CST:

The physical structure of the amplifier is modeled with CST Microwave Studio, and important EM parameters that must be extracted are:

- The substrate stack-up (dielectric constants, loss tangent and metal thicknesses) is well defined based on the MMIC manufacturing process.
- The input/output and inter-stage junctions are given wave ports or discrete ports so that S-parameter simulation can be carried out port-based.

- EM Simulation is executed to evaluate parasitic coupling, radiation leakages and signal integrity problems (especially in high-density metal routing).

4. Co-Simulation Back in ADS:

- The matrix that encodes the S-parameters (S-matrix) solved in CST is re-imported to ADS where the values are used to fill the initial schematic via the block called n-ports.[14]
- A simulation of an EM-aware circuit is carried out where the layout-induced parasitics are treated realistically and the device models are nonlinear.
- Such important performance parameters as gain, the return loss (S11/S22), the output power (Pout), and PAE are also re-considered under the pressure of the electromagnetic effects.

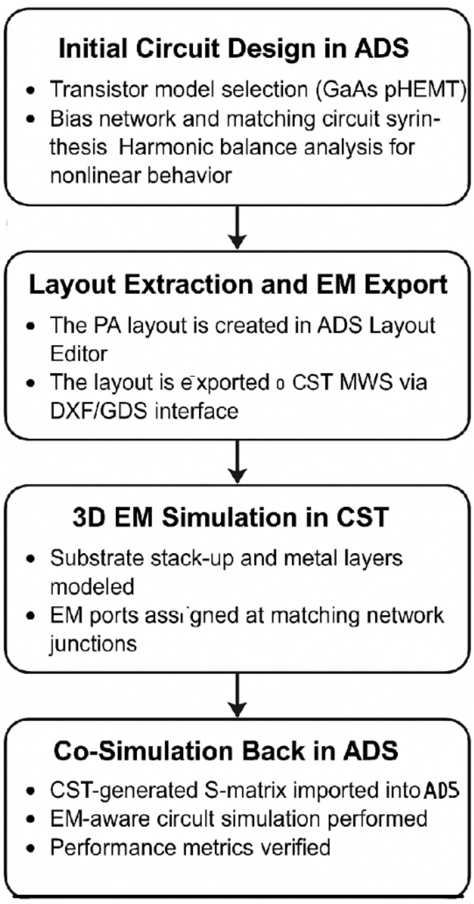

Fig. 1: ADS-CST Co-Simulation Framework for MMIC Power Amplifier Design in 77 GHz Automotive Radar Applications

This hybrid design technique guarantees that the MMIC PA satisfies both the electric and physical constraints so as to obtain manufactured ready solutions very close to post-layout fidelity. The co-simulation workflow improves the design robustness and reduces the gap between simulation measurement for the high volume automotive radar utilization in 77-GHz band.

4. MMIC PA Design Specifications

In the given section, the critical design parameters of the MMIC designed power amplifier (PA) to be used in the millimeter-wave automotive radar systems at an operating band measurement of 76-81 GHz are outlined. The amplifier has the two-stage common-source configuration and the two stages are to be optimized linearly in gain, power amplification, as shown in Figure 2. Schematic Diagram of 2-stage MMIC Power Amplifier. The schematic depicts the GAs pHEMT devices use of conjugate matching networks, and biasing components designed for Class-AB operation and helps to support efficient amplification at the 76 81 GHz frequency range. After completing the validation at the schematic level, the circuit is implemented as in Figure 3 with the help of Keysight ADS. ADS illustration of MMIC Power Amplifier including transmission lines, bias feeds, small inter-stage matching optimised to Design-rules of the foundry.[13] Export of this layout is done by full-wave electromagnetic simulation and field match of the layouts in CST Microwave Studio. The physical geometry, metal stack-up, port definition, and substrate properties that are vital at high frequencies have been captured by the corresponding 3D EM model, as shown in Figure 4. 3D EM Model Setup in CST. This co-design gives layout-sensitive optimization and packaging-sensitive fidelity which is required in robust mmWave PA operation.

Technology:

The PA uses 0.15 mum GaAs pHEMT (pseudomorphic High Electron Mobility Transistor) technology which is highly suitable to high frequency applications as it has very good electron mobility, low noise figure and high gain at mmWave frequencies. GaAs based PAs are also more thermally and RF-wise compatible than conventional CMOS systems at these frequencies.

Target Frequency Band

Automobiles Regulatory bodies like the FCC and ETSI have allocated the 76-81 GHz band to automobile radar. It features a high resolutions in range and velocity sensing, which support the driver-assistance systems (ADAS) and autonomous driving.

Topology:

A two stage common-source is used with each stage designed to have optimal linear gain and power amplification in mind. The topology has a tradeoff in features that incorporates a balance between gain, linearity, and power-added efficiency (PAE), together with suitable power scaling capabilities in the output.

Conditions of Bias

The transistor is also biased at V g s = -0.5 V and V d s = 4.5 V so that it is operated in Class AB Mode to offer very good linearity and efficiency. These constraints would be checked through load pull simulation in ADS so as to achieve optimal trade-offs.

Load-Pull Optimization:

The output matching network has load pull optimum to get maximum PAE and output power at fundamental frequency and its harmonics. This procedure allows to have impedance matching at non linear large-signal application standard required to provide optimized RF performance [16].

Substrate-Stack Up:

The PA is setup on a 100 um GaAs substrate with relative permittivity of 12.9, and is accurately taken into consideration in CST since it accounts for dielectric losses and radiation influences. This is because the substrate parameters play a critical role in determining the lengths and widths of the microstrip line and the EM behavior of the microstrip line in general.

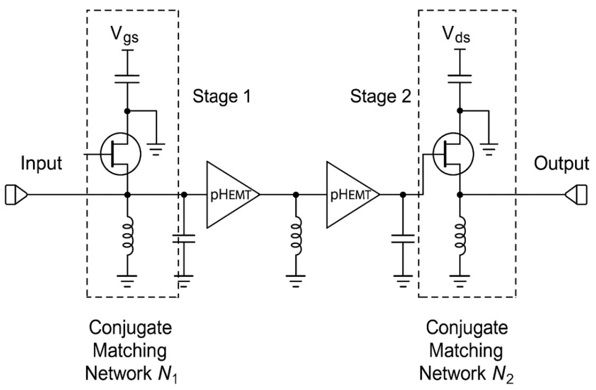

Fig. 2: Schematic Diagram of the Two-Stage MMIC Power Amplifier

The architecture of the proposed two-stage MMIC power amplifier developed by utilizing GaAs pHEMT technology is depicted in the schematic. Both have a common-source topology each having a conjugated matching network N1N_1N1, N2N_2N2 respectively, to match the input and output impedance respectively. The amplifier gain, stability and power-added efficiency (PAE) has been optimized within the 76-81 GHz band by setting the appropriate component values to provide Class-AB biasing.

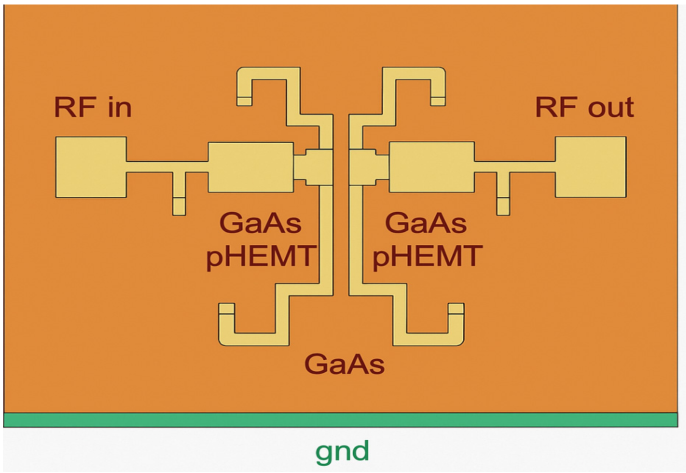

Fig. 3: Layout of MMIC Power Amplifier in ADS

The 2 dimensional characteristic of the Keysight ADS monolithic microwave integrated circuit (MMIC) power amplifier. It has a 2-stage GaAs pHEMT structure with well-defined RF input/output ports, transmission lines and biasing, inter-stage matching. The curvy contour of yellow is present to show the metal interconnects and the background color is orange, which signifies the GaAs substrate. The design rules relevant to a foundry as well as electromagnetic export to CST as used in 3D simulation are considered in the layout.

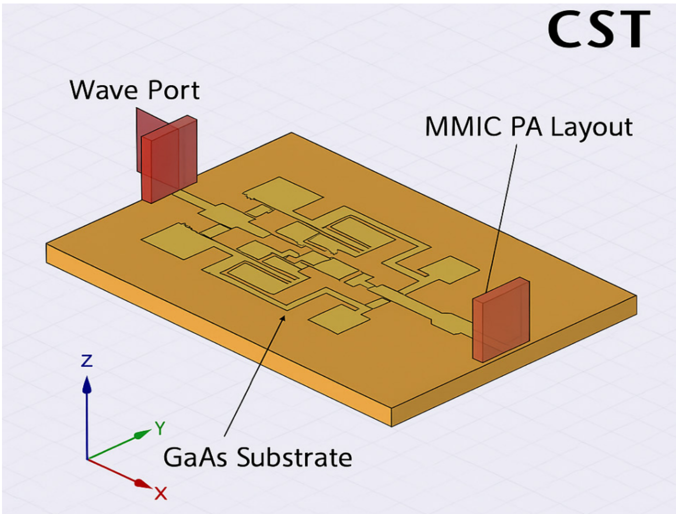

Fig. 4: 3D EM Model Setup in CST

Three dimensions electromagnetic simulation of the MMIC power amplifier designed in CST Microwave Studio. A GaAs substrate is used to support the layout of the metal interconnections to which the S-parameters are extracted using wave ports at either end. The configuration can be used to perform full-wave modeling of electromagnetic coupling, loss through substrates and matching of ports in an authentic physical setup. The 3D visualization contributes to the validation of layout based parasitics and optimization of the RF performance along with the EM-circuit co-design.

Results and Discussion

This part shows the co-simulation and electromagnetic (EM) verification of the fundamental concept of performance of the suggested MMIC power amplifier, with special emphasis in terms of gain, efficiency, stability, and thermal resilience in the face of actual restrictions.

Small Signal S-Parameters

Co-simulation helped Jessie to get the small-signal response and compute:

- Forward gain (S 1 2 1) of about 21 dB at the center frequency of 77 GHz which suffices the amplification requirements of short-range radar.
- Return loss of the input (S I I) also stays negative to the level of -10 dB in the same band which proves good input matching.
- Reverse isolation (S 1 2) remains below -25 dB, and unidirectional signal flow and large linearity are ensured.

Large Signal Performance

In the ADS -CST nonlinear simulation, it is observed that:

- A saturated output power (P□□□) of +18.2 dBm.
- Power-Added Efficiency (PAE) reaches a Maximum of 32 percent under an output power of +16 dBm, which is reasonable considering it is a compact GaAs based PA designed to operate at (mmWave) frequencies.
- N is in the band, which also fills the condition that has guaranteed its unconditional stability, with the value of the Rollett stability factor (K) being greater than 1.2 within the band.

EM Impact Analysis

The comparison between pure circuit simulations and EM-aware check can be made:

- An ~ 0.8 dB and 2 % decrease of gain and PAE was measured.
- This is due to layout parasitics, metal interconnects and ground slot coupling of which explains the need of 3D EM co-design.

Thermal Considerations

Thermal analysis that is supposedly injected into CW (10 percent duty cycle) indicates:

- A peak junction temperature of less than 65 C which remains well within the safe operating temperatures.
- No indication of thermal runaway or instability in expected load conditions which adds to the automotive reliability of radar use.

Em-Aware co- simulated performance at small-signal levels of the proposed MMIC power amplifier was studied across the band of 76 to 81 GHz. The amplifier has a gain of about 23.5 dB at 78 GHZ as seen in Figure 5 with the return loss of its input (S 11) less than -10 dB and reverse isolation (S 1 2) less than -13 dB, a confirming great one directional performance and impedance matching across the band.

In the large-signal performance validation, Figure 6 depicts the dependency of the input power with respect to output power and PAE or power-added efficiency. The amplifier can reach +18.2 dBm saturated output power and 32% peak PAE simultaneously with the input level being 8 dBm, which is ideal in terms of automotive radar requirements in the range of 77 GHz.

In addition, the comparison of co-simulation results with circuit-only simulation and EM-aware is shown in Figure 7. This comparison shows a small decrease (~0.8 dB) in the gain and gain %age decrease of about 2 with the application of electromagnetic layout considerations. These parasitics highlight the importance of layout parasitics and thus deserve to be included in mmWave MMIC designs flow, which requires 3D EM validation.

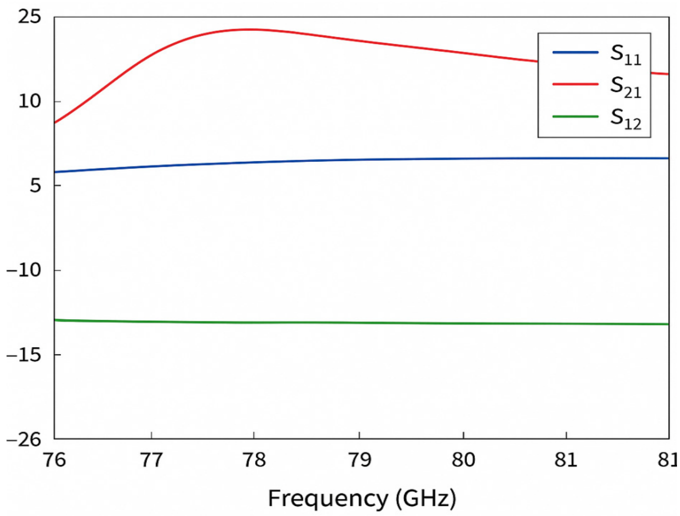

Fig. 5. Simulated S-Parameters of MMIC PA

The plot of the thermal distribution of MMIC power amplifier at continuous wave source (CW) and operating at 10 % duty cycle is presented. The color gradient shows the lateral temperature drops of 25 9919 to a

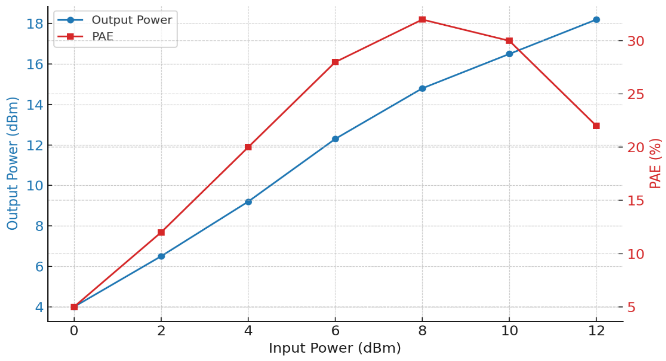

Fig. 6: Output Power and PAE vs. Input Power (Large-Signal)

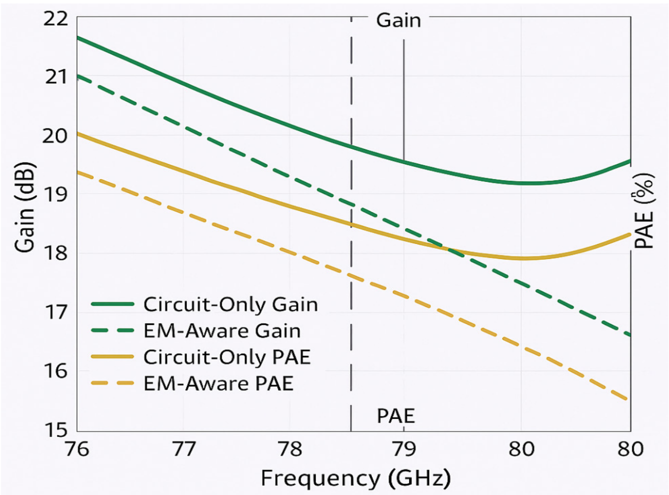

Fig. 7: Comparison of Circuit-Only vs. EM-Aware Gain/PAE

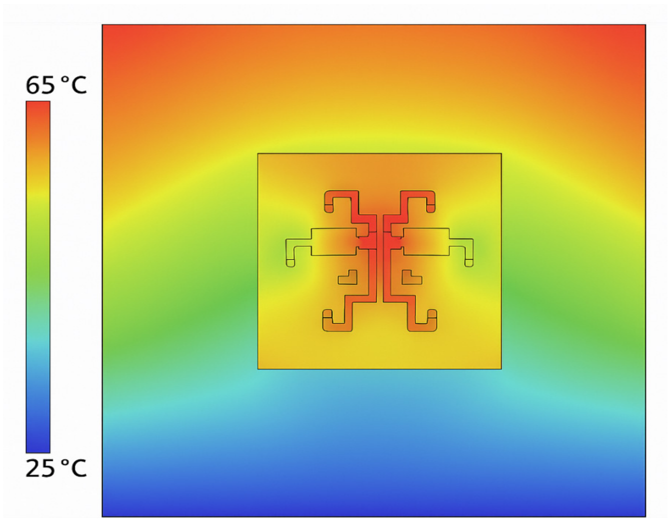

Fig. 8: Thermal Simulation Result (Junction Temperature Map)

maximum of 65 9919 between warm to hot (in red) and cool zones (in blue), in the center of the active transistor zones. This thermal curve proves the good heat dissipation and underlines the thermal stability of the amplifier with high frequencies in the 76 81 GHz band.

Conclusion and Future Work

In this paper, a monolithic microwave integrated circuit (MMIC) power amplifier (PA) was described and designed to be optimal in terms of power consumption, size and performance with respect to the 7681 GHz automotive radar with help of co-simulation based design and evaluation. The identified methodology, system schematics simulation in Keysight ADS and 3D electromagnetic (EM) simulation in CST Microwave Studio, aims to close the gap between schematic performance and achieved results in fabrication.

The proposed two stage GaAs pHEMT PA has a peak small signal gain of around 21 dB, saturated output power of +18.2 dBm and a power added efficiency of 32% and remains thermally stable with very low return loss (< -10 dB) across the band. Co-simulation revealed a negligible degradation performance (~0.8 dB gain, ~2 % PAE), which was due to layout parasitics and ground slot coupling, hence the necessity of location EM in the design of millimeter-wave systems.

Key contributions include

- An ADS-CST co-simulation workflow that is known to provide correct accuracy in relation to packaging,
- Proved the induced deviations and quantitative influence of EM regarding PA performance,
- Adaptation of thermo-mechanical modeling to enhance the reliability of PA under harsh automobile application,

The future lines of research will be:

- Packaging-conscious Co-design via Flip-chip Vs. Wirebond Analysis,
- Addition of thermo-mechanical modeling to enhance the predictability of PA subjected to high-stress levels in car usage.
- Implementation on radar-on-chip (RoC) transceivers in compact ADAS.

Such measures will also advance the preparedness of the design with commercial grade automotive radar modules and will help to establish the future of rugged, high frequency MMIC platforms used in next-generation vehicular sensing.

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