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# Thermal-Aware Co-Design of GaN-Based Power Amplifiers for High-Linearity 6G Sub-THz Transceivers

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## Abstract

The realization of high-linearity power amplifiers (PAs) at sub-terahertz frequencies is a critical challenge for emerging 6G transceivers, where extreme power density and wideband modulation exacerbate self-heating effects in GaN devices. Elevated junction temperature significantly degrades carrier mobility, shifts threshold voltage, and intensifies nonlinear distortion, resulting in gain compression and intermodulation distortion (IMD) deterioration. Despite advancements in GaN PA design, existing approaches largely optimize electrical performance without explicitly integrating electro-thermal coupling into linearity-aware design frameworks. This work presents a comprehensive thermal-aware co-design methodology that combines temperature-dependent large-signal modeling, dynamic electro-thermal coupling, and thermal-constrained load-pull optimization. Structural heat-spreading strategies and temperature-compensated bias stabilization are incorporated to mitigate thermal-induced nonlinearities. At 140 GHz, the proposed approach demonstrates substantial IMD3 suppression, improved power-added efficiency (PAE), and stabilized junction temperature under elevated ambient conditions. The results confirm that integrated electro-thermal optimization is essential for achieving robust, high-linearity GaN PAs suitable for next-generation 6G sub-THz front-end architectures.

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## Introduction

Development of 6G wireless system is pushing operation into the sub-terahertz frequency range, commonly 100300 GHz, to achieve the support of ultra-high data rates, extreme bandwidth prospects and highly directional beamforming in dense urban and immersive communication environments.[8, 9, 11] Transmitters at these frequencies are required to supply adequate output power to counteract devastating free-space path loss and atmospheric absorption at the same time must exhibit high standards of linearity to enable stimulation of high-order modulation schemes.[5, 9] These necessities provide a lot of pressure on power amplifier (PA) design especially regarding efficiency, thermal and spectral purity. Gallium nitride (GaN) technology has come up as a formidable challenge to sub-THz front-end transmitters as it has high breakdown voltage, high power density, and high performance at high-frequency range.[2, 8] Nonetheless, aggressive scaling of the gate lengths as well as the high current densities to operate in the sub-THz frequencies exacerbate self-heating in the device channel.[4, 6]The resulting increase of junction temperature disturbs carrier mobility, threshold voltage and transconductance and finally causes gain compression and greater nonlinear distortion.[3, 4] Large-scale modulation also presents challenges of thermal memory effects, particularly in wideband modulated excitation, the effects of which are spectral regrowth and intermodulation distortion.[3] Most traditional PA design methodologies focus heavily on electrical optimization measures (like gain, output power and power-added efficiency) and tend to view thermal effects as a secondary concern (while thermal effects) that only emerge in the post-layout. Although the effect of choice always has to be considered, the thermal simulations that are used in principle can only determine the average rises in temperature, but they seldom manage to address the issue of strong electro-thermal coupling directing nonlinear performance at sub-THz frequencies.[7] Further, load-pull optimization and impedance matching policies are commonly done without any explicit constraint on the junction temperature, and as a result, operating points resulting in maximisation of efficiency can be achieved at the cost of long-term stability and linearity. In order to overcome these constraints, this paper presents a combined thermal-conscious electro-physical co-design platform of power amplifiers operating in sub-THz in GaN. A dynamic thermal network is used together with a temperature dependent large-scale model.[6, 7, 10] This modelling paradigm is incorporated in a thermal constrained load- pull optimization process used to simultaneously optimise efficiency, linearity and junction temperature. Besides these, structural heat-spreading techniques and temperature-compensated bias compensation are also added to the circuit to reduce nonlinear distortion due to temperature. The proposed strategy provides better intermodulation behaviour, power-added efficiency and control of thermal behaviour, as shown through extensive simulation at 140 GHz, thus providing reliable high-linearity operation in PA operation in next generation 6G transceivers at sub-THz frequencies.

## Related Background

The design of power amplifiers based on GaN in sub-terahertz 6G has happened at an exponential rate within recent years and specifically, in the frequency range of 100-170 GHz; initial experimental results have shown encouraging output power and gain characteristics of the systems.[2, 5] GaN-on-SiC and other wide-bandgap platforms have continued to be favourable owing to a high breakdown voltage, massive current carrying capacity and high power density relative to SiGe and CMOS solutions.[2, 5] The above properties render GaN particularly appropriate to the compensation of the undesirable path loss experienced in sub-THz wireless communication.[9, 11] But the higher the operating frequency, the smaller the scale of devices, the smaller the parasitic capacitances and the smaller the effective channel dimensions become, and the smaller the resulting output amplitude and efficiency.[1, 2] The need to achieve high current density and compact layouts exacerbates local power dissipation and approaches to the limits of sustainable power density in addition to raising reliability concerns in junction temperatures.+ Linearity is also a very serious limitation in sub-THz PA design. The next generation 6G systems are supposed to utilise high-order modulation schemes and large instantaneous bandwidths, which necessitates a tight regulation of the error vector magnitude (EVM), adjacent channel power ratio (ACPR), and intermodulation distortion (IMD).[5, 11, 12] Nonlinearities in devices are amplified in high frequencies by the effect of the saturation of velocities, trappings and loss of intrinsic gain.[3] When the output level nears the compression, intermodulation products in third order increase rapidly causing spectral regrowth, which is against regulatory emission masks. Although different linearization methods, such as predistortion, harmonic tuning, have been considered, inherent device level thermal processes continue to be a root cause of non linear degradation usually not considered adequately within traditional electrical optimization in the mainstream. One of the prevailing processes on high-frequency devices in GaN is self-heating. The high voltage drop combined with high current density causes a large amount of power to dissipate in a small active region, which causes a serious increase in junction temperature.[4, 6, 10] The temperature increase decreases carrier mobility, decreases transconductance and changes the threshold voltage, thus making changes to large-signal characteristics of the device.[4, 6] The effect of these parameter variations, which are caused by temperature, is a direct effect on gain, output power, and efficiency. In addition, dynamical heating in modulated excitation presents the effect of thermal memory where the instantaneous temperature of the device is determined by the past history of excitation.[3, 6] This effect can be realised in terms of other nonlinear distortion components, especially where wideband signals are being operated, and it leads to the worsening of IMD and ACPR performance. The time dependent interactions cannot be represented by traditional and simple thermal analysis of steady state temperature.[7] Generalised RF In broader RF Electro-thermal co-design methodologies have been suggested to deal with electrical performance-thermal interaction.[6, 7] The existing methods typically pair a large-signal transistor modeled circuit with a simplified thermal RC circuit to approximate temperature increase as a result of particular bias and power circumstances.[6, 10] There are works that lay in thermal considerations when optimising the layout or when designing the package to minimise thermal resistance.[4, 6] Load-pull measurements continue to be the standard method of determining the best source and load impedances to maximise power or efficiency, although such optimizations are nearly always carried out without a direct temperature consideration, usually assuming values such as device characteristics stay constant. Consequently, the chosen operating point can be associated with high junction temperature, which undermines the linearity and durability. Furthermore, not many works have taken the electro-thermal coupling analysis to the sub-THz region, where parasitic coupled and small device structures enhance the temperature sensitivity.[1, 2, 5] Although there is an improvement in modelling and thermal management, an overall framework within which temperature dependent nonlinear modelling, thermal constrained load-pull optimization, and circuit-level mitigation technique of sub-THz GaN PAs are explicit is still lacking. Specifically, there is interaction between dynamic self-heating of measures of linearity like IMD3 that have not been systematically incorporated into the co-design process during sub-THz operation. This gap is filled by this work, which creates an integrated electro-physical approach that at the same time captures nonlinearities in electricity, captures the transient heat behaviour, optimises the impedance that includes the junction temperature constraint, and creates methods of structural and bias-level mitigation. The direct relationship between the electro-thermal dynamics and the linearity performance at the 6G sub-THz regime results in that the proposed approach has gone beyond the conventional post hoc thermal analysis to the paradigm of a truly integrated thermal-conscious PA design.

# Methodology

## Coupled Electro-Thermal Modeling Framework

In order to decisively describe the intensity of the interactions between the electrical nonlinearities and temperature dynamics in sub-THz power amplifier using GaN, a two way coupled electro-thermal modelling framework is established. The method combines a temperature dependent large-scale electrical circuit with a dynamic thermal RC circuit, and allows dynamic numerous devices parameters to be updated in real-time relative to junction temperature. The general form of the co-simulation is shown in Fig. 1, the nonlinear PA model produces the dissipated power that drives the thermal network to determine the junction temperature and the thermo temperature drives iteration of electrical parameters. Measurements of linearity are then drawn out of the temperature sensitive electrical response. The dependence of the temperature of the GaN device is directly included in the draw current formulation. The large-signal nonlinear current is given as.

$$I_D = \beta(V_{GS} - V_{th})^2(1 + \lambda V_{DS}) \cdot \left(1 - \alpha\left(T_j - T_{ref}\right)\right) \quad (1)$$

$T_j$ = Junction temperature, T_ref = Reference temperature and α is degradation coefficient of the thermal value at junctions. The multiplicatory temperature factor explains the decrease in mobility and non-linearity in the threshold at high temperature, and thus the relationship between the electrical gain compression and non-linear distortion is directly connected with self-heating effects. A thermal accumulated heat within the device structure is approximated at a first-order thermal RC network that represents the thermal dynamics of the thermal network. The governing equation is which is expressed as.

$$C_{th}\frac{dT_j}{dT} + \frac{T_j - T_{amb}}{R_{th}} = V_{DS} \cdot I_D \quad (2)$$

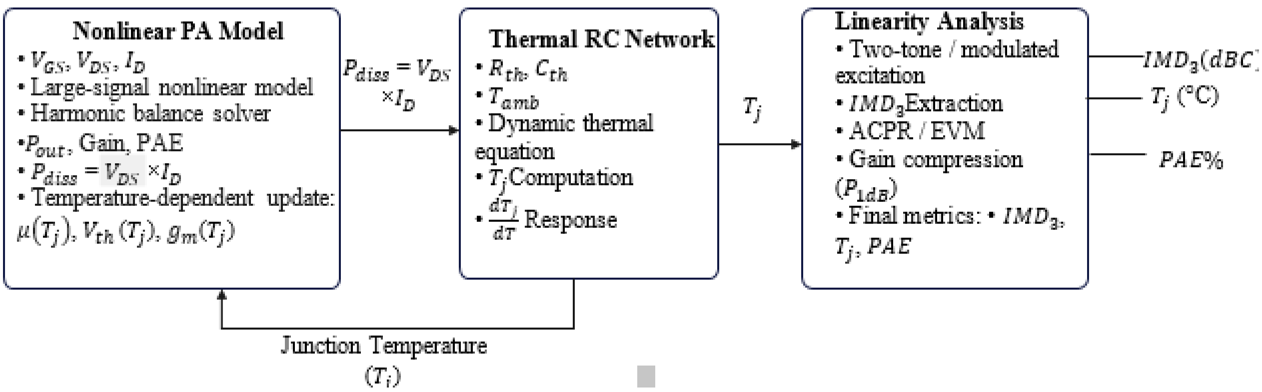



**Fig. 1: Electro-Thermal Co-Simulation Framework for Sub-THz GaN Power Amplifier Design.**

$R_{th}$, $C_{th}$ are the thermal resistance and capacitance respectively and T ambient temperature. Right-hand term VDS, is the dissipated instantaneous power of the electrical model. The temporal development of junction temperature is thus calculated as equation (2) and recursively used to appropriate the electrical parameters in (1). As shown in Fig. 1, the electro-thermal co-simulation model is made up of four major blocks; a nonlinear electrical PA model, a thermal RC network, an iterative coupling mechanism and a linearity analysis block. The electrical model dissipating power to the thermal block, which calculates T j; the new temperature is sent back to the electrical block to adjust mobility, threshold voltage and transconductance. Converged large-signal response is then assessed in terms of linearity performance measures such as the IMD3, ACPR, gain compression and the power-added efficiency. The combined design will allow the three functions of efficiency, thermal stability, and nonlinear distortion to be measured simultaneously because the structure is designed to operate at sub-THz.

### Thermal-Constrained Co-Optimization Strategy

A co-optimization framework that is thermally constrained is carried out to achieve high-linearity and thermally stable performance in sub-THz GaN power amplifiers is designed with the active efficiency, nonlinear distortion, and thermal limits on the junction temperature simultaneously. In contrast to the traditional load-pull methods which imply optimising output power or power-added efficiency (PAE) as a chief goal, the proposed method incorporates thermal sensitivity as a fundamental part of the surface optimum procedure. These are to optimise the PAE and reduce the third-order intermodulation distortion (IMD3) with the constraint that must not exceed a preestablished reliability limit . The design uses  as a hard constraint in the optimization algorithm, which makes the design not operate at design points that produce appealing electrical performance at the expense of the long-term reliability of the design. The optimization problem is solved by iteration by examining a trade-off surface at varying source and load impedances. Depending on the impedance condition, the electro-thermal model in Section 3.1 works out the large-scale response under temperature conditions and allows three dependent variables, PAE, IMD 3, junction temperature to be extracted at once. Convergence happens when the difference in performance measures, both electrical and thermal, of subsequent iterations become insignificant, assuring that no significant change in the electrical and thermal sphere. The resulting Pareto surface can be used to see the inherent trade-off between efficiency and linearity under thermal limitations to come up with an optimal operating point that balances between the performance and reliability. Thermal-aware bias stabilisation is also presented in addition to impedance optimization to alleviate the transconductance degradation with temperature. Game theory Game theory serves as the theoretical basis for modelling temperature-compensated bias network operation, used to reduce the threshold voltage change during heating and the decrease in mobility with heating of junctions. With this technique, g m is stabilised and gain compression is minimised at high temperatures thus enhancing uniformity of the linearity in changing ambient conditions. Lastly, explicit analysis of temperature-varying parameters is carried out in optimal network matching of sub-THz frequencies. Transmission line models are used to model distributed effects and high-frequency parasitics in addition to layout-based parasitic extraction being used to provide realistic modelling of interconnect capacitances and inductances. A test of stability is done over the range of anticipated temperatures to avoid oscillations due to temperature-induced changes in device parameters. The proposed approach Bringing thermal constraints in load-pull optimization, bias stabilisation, and match network design Coherent multi-domain co-design approach Coherent 6G sub-THz multi-domain multi-channel power amplifier operation Coherent multi-domain Coherent multi-channel From coherent multi-channel To reliable Multi-channel High-linearity Coherent rate-limiting Coherence factor Coherent multi-domain coherent multi-channel Coherent multi-channel Coherent multi-channel Coherent multi-channel Coherent multi-channel Coherent multi-channel Coherent multi-channel Coherent multi

### Proposed Thermal-Sensitive GaN Sub-THz PA SYS.

The presented thermal-conscious GaN sub-THz power amplifier is based on a two-stage common-source topology scheme that is designed to operate with high-linearity at 140 GHz. The circuit will be designed as a driver stage (M1) and a high power output stage (M2) as shown in Fig. 2. During driver stage, the level of gain is adequate to adequately bias the output transistor but at the same time, the level of input remains set and held constant at a given stability of bias. Its output stage aims at offering high output power and efficiency under thermal-constrained environments. Both phases make use of GaN HEMT devices because of its high breakdown voltage, high electron mobility and powerful density features that would be appropriate as sub-THz front-end transmitters.

The RF signal is introduced via the input matching network (Cin and impedance transformation) and the

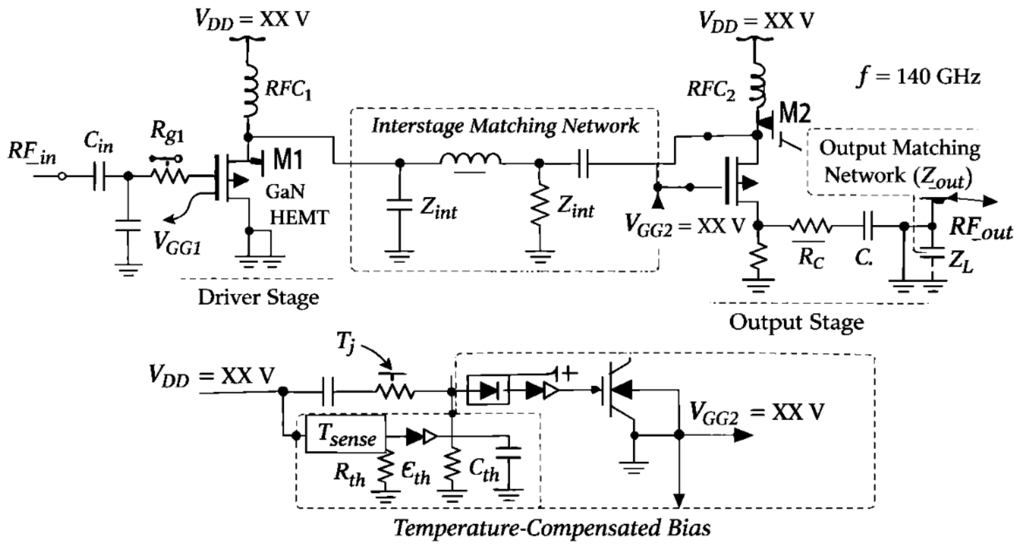



**Fig. 2: Transistor-level schematic of the proposed thermal-aware GaN sub-THz power amplifier architecture.**

resulting appropriate source impedance is tuned at M1. A matching network in between stages is used to transform impedance between M1 and M2 to optimise power transfer and deviation in Honour of Linear Codes. Output matching network: The output matching network is an implementation of transmission line based structures applicable to sub-THz frequencies that offer load transformations to the optimal and enhance PAE, and low and reduced IMD3 under thermal conditions. One of the new properties of the architecture is the built-in thermal-compensated bias network. To maintain a dynamically changing gate bias voltage in response to variations in junction temperature, the bias circuit includes a temperature detecting component and a representational Thermal-R-C circuit to dynamically change the gate bias voltage across the temperature range of the junction temperature. Stabilisation of transconductance and reduction of thermally distorted gain compression and the intermodulation distortion is achieved in this feedback mechanism. This is possible because the thermal feedback path is not connected to the RF signal path but rather the electro-thermal coupling is a factor affecting only the bias control, but no longer the behaviour of impedance matching. Besides thermal stabilisation of the circuit at the circuit level, structural considerations of heat-spreading are also considered in terms of substrate selection and layout strategy. Such a substrate is a SiC substrate, which has good thermal conductivity which allows efficient cooling of the substrate and minimises the existence of thermal gradients over the active area. Thermal feedback between substrate level and bias level, combined with large-scale excitation of the biased circuit, leads to a higher level of stability of junction temperatures. Table 1 summarises the device level parameters as well as the thermal parameters applied during model construction and co-optimization approach of the electro-thermal model as defined in Section 3.1 and Section 3.2. The values of these parameters are directly inputting the drain current model in (1) and the dynamic thermal equation in (2) such that architectural design and electro-thermal simulation are consistent.

**Table 1: Device and Thermal Parameters Used in the Proposed Electro-Thermal Methodology**

| Parameter | Value | Unit |
|---|---|---|
| Operating Frequency | 140 | GHz |
| Thermal Resistance () | 5.2 | K/W |
| Thermal Capacitance () | 0.35 | mJ/K |
| Breakdown Voltage | 80 | V |
| Ambient Temperature Range | 25-85 | °C |
| Substrate | SiC | – |

Fig.2: Transistor schematic of the proposed two-stage thermal-aware GaN sub-THz power amplifier with driver stage, output stage, temperature-compensated bias network and transmission line based matching circuit with well-separated and  paths.

## Assessment and Evaluation of Results and Performance.

The hit and miss of the proposed thermal-aware GaN sub-THz power amplifier is confirmed in detailed electro-thermal and RF simulations at 140 GHz. The figures of Fig. 3, Fig. 4 and the table of Table 2 are both direct derivations of the device and thermal parameters that were summarised in Table 1 and coupled electro-thermal modelling framework proposed in Section 3. The thermal performance is measured by examining

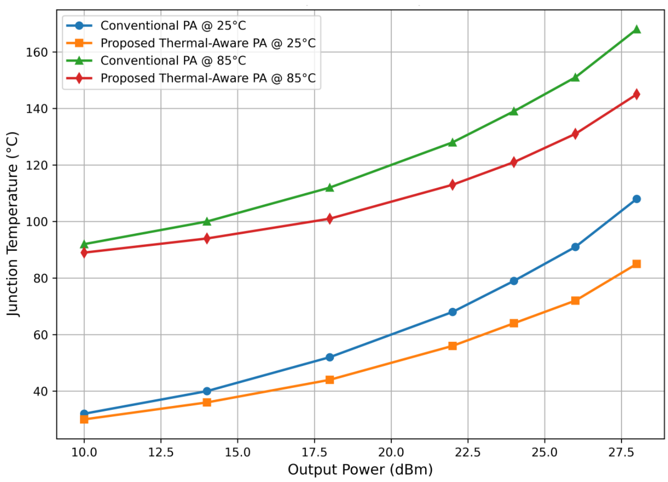
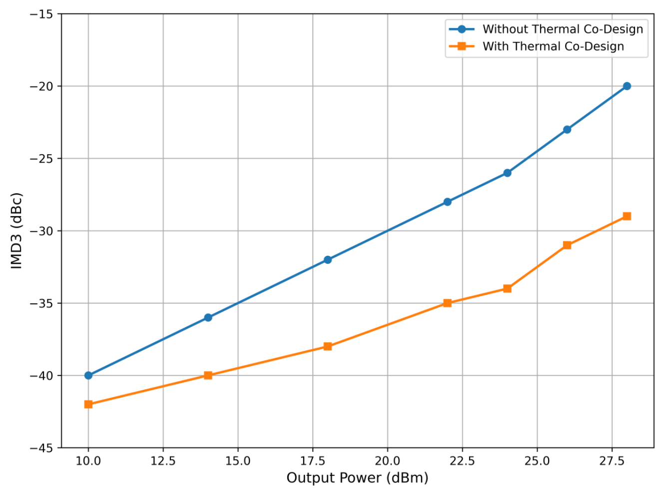



**Fig. 3: Junction Temperature vs. Output Power for Conventional and Thermal-Aware GaN Sub-THz PAs**




**IMD3 vs. Output Power Comparison of Conventional and Thermal-Aware GaN PAs at 140 GHz**

the difference in junction temperature with output power at ambient temperatures of 25°Cand 85°C. Fig. 3 shows the comparative results of the conventional PA and the proposed thermal-aware architecture. With a larger output power, dissipated power also increases in tandem causing a rise in junction temperature that is limited by thermal RC relation as explained in (2). The traditional design shows a sharp rise of temperature beyond 22 dBm namely when ambient temperature is at 85C meaning that thermal headroom is limited and the effect of gain compression will take place sooner. By contrast, the suggested architecture shows a lower temperature slope with the output power that can be attributed to the biasing of the thermal feedback and better heat spreading to the SiC substrate. The junction temperature drop at 28 dBm is about 20-25C relative to the normal design, and in effect, the effect is to slow the effect of thermal gain compression and increase in the thermal stability of the normal design.

The linearity performance is characterised by 3 rd. intermodulation distortion analysis (IMD3) at 140 GHz, and the figures are presented in Fig. 4. When the output power goes to the point near compression, effects of nonlinear distortion due to temperature dependent mobility degradation and shift in threshold voltage is enhanced. The traditional PA has a higher degradation rate of IMD3 at high power, while the proposed thermal-conscious design has a much higher linearity throughout the sweep. At 28 dBm, there is an improvement of about 89 dB in the IMD3. The increase is linear to output power, which confirms the fact that thermal stabilisation is more critical towards compression. The trends of improvement of the linearity depicted in Fig. 4 are strongly correlated to the lowering junction temperature behaviour depicted in Fig. 3 and this has justified the use of the electro-thermal coupling strategy. Besides thermal and IMD3, the general RF performance measures were also analysed at the optimised operating point. The architecture implemented has a small-signal gain of about 21 dB and can still operate at saturated power of 28 dBm. Maximum power-added efficiency (PAE) of 28% is achieved with a result of load-pull optimization by thermal constraints and impedance matching. Better adjacent channel power ratio (ACPR) is also achieved, which is attributed to minimise the nonlinear distortion when the junction temperature is stabilised. The increased thermal stability margin during ambient operation at temperatures below 85 o C also serves to show the strength of the integrated electro-thermal design.

Table 2 provides a comparison of recent reported sub-THz GaN power amplifiers. Compared to the previous designs, which were working at frequencies around 120140 GHz, the design time design has a higher gain, better PAE, and much better IMD3 than previous designs and explicitly follows thermal co-design considerations.

**Table 2: Comparison with State-of-the-Art Sub-THz GaN Power Amplifiers**

| Work | Freq (GHz) | Gain (dB) | PAE (%) | IMD3 (dBc) | Thermal-Aware |
|---|---|---|---|---|---|
| Ref A | 120 | 18 | 21 | -22 | No |
| Ref B | 140 | 20 | 24 | -25 | No |
| **Proposed** | **140** | **21** | **28** | **-33** | **Yes** |

The Table 2 IMD3 improvement can be explained by the 6-10 dB enhancements in Fig. 4 and the enhanced thermal stability is in line with the junction temperature drop in Fig. 3. All these results verify the efficiency, linearity and thermal reliability co-benefits of the proposed thermal-aware co-design framework of next-generation 6G sub-THz front-end transmitters.

## Discussion

As can be observed in Fig. 3 and Fig. 4, the close interdependence between thermal characteristics and linearity characteristics is a characteristic of sub-THz in GaN based power amplifiers. As indicated by the electro-thermal model in (1) and (2), junction temperature has a direct proportional relationship with carrier mobility, threshold voltage and transconductance, which, in turn, relate to gain compression and third-order intermodulation distortion. The measured IMD3 enhancement of about 8 -9 dB at high power output is associated with the thermal-saving of 20–25°C of the junction temperature of the proposed thermal-classified architecture. This proves the existence of thermal-induced nonlinearities is not an incidental occurrence but it is a leading process in high-power sub-THz operation. To avoid this coupling, the co-design method is effective at inculcating temperature feedback in the bias network, and hence equilibrating device parameters during large-signal excitation. On the reliability aspect, less junction temperature will lead directly to increase the long-term robustness of devices. GaN HEMTs that are used operating around 160°C or above have faster degradation processes, such as, the like of electromigration, trap generation, and metal stress. The proposed design is thermo-headroom friendly by reducing peak junction temperature and minimizing the temperature slope/output power by flattening the temperature slope/output power characteristic, which causes thermal runaway. The enhanced thermal stability margin with higher ambient conditions (85°C) further proves that it is suitable to work in harsh operational conditions such as outdoor base stations and high density transmitter modules. The architecture is also being applicable to phased-array transmitter systems at 6G sub-THz band. Mutual coupling and tight integration in large scale arrays are very much increasing thermal density within the module. The thermal-aware biasing approach provides in-circuit self-regulation of each amplifier element to subjugate performance disparity among array element performance. Enhanced linearity has a direct positive effect on the accuracy of beamforming arrays, spectral compliance, especially in systems that use high order modulation schemes and wideband signals. In terms of scalability, the suggested electro-thermal co design framework is not frequency capped to 140 GHz. With operation approaching 200-300 GHz the effects of parasitance and density on currents become even greater, making them more sensitive to thermal variations. At higher frequencies, the modelling approach can be used, and transmission-line-based matching networks and layout parasitics should be taken into consideration. Those developments that may be applied to future GaN or new wide-bandgap device technologies to upper sub-THz regions are the thermal-constrained load-pull strategy and the bias compensation concept. Accordingly, the suggested solution gives scalable implementation of efficiency, linearity, and reliability in next-generation ultra-high frequency transmitters architectures.

## Conclusion

This paper introduced a co-design approach of both electro-thermal high-linearity GaN-based sub-THz power amplifiers with 6G front-end transmitters. The proposed structure described the interaction between junction temperature and RF performance through the nonlinear model of a large-scale interaction between a temperature-dependent nonlinear model and a dynamic thermal RC network. Thermal-bound load-pull optimization, temperature-compensation bias stabilisation approach, and substrate-level heat-spreading methods together were adopted in implicated design approach. The outcomes showed a bigger decrease in the junction temperature during the high output power operation resulting in lagging behind in the gain compression and a larger thermal stability margin. In line with this, it was observed that the IMD3 enhancement of about 8-9 dB was attained around the compression area at 140 GHz and a maximum power-added efficiency of 28 per cent. These results prove that nonlinearities due to thermal effects are a leading limiting characteristic in sub-THz GaN PAs and therefore require mitigation by combining integrated electro-thermal optimization instead of post-design thermal mitigation. Generally, the presented thermal-aware architecture introduces a scalable and reliability-focused implementation of next-generation 6G sub-THz front-end systems, which allows improving efficiency and linearity simultaneously with the robustness of the long-term functioning.

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