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Ruggedized RF Transmitter Design for High-Temperature Aerospace Environments

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Abstract

The growing need to have reliable wireless communication systems in the aerospace platforms also requires the need to have RF transmitter architecture that can maintain its capability to operate under the extreme environment especially the high temperature and radiation environment. This paper gives full design, modeling and validation of a ruggedized RF transmitter that can be used with aerospace environment where ambient temperatures can reach a high temperature of 250C. The main building block of the proposed architecture is a power amplifier based on GaN that is predicted to have better heat tolerance and higher power ratings than silicon- or gallium arsenide-based predecessors. The system is thermally stable with temperature-compensated biasing circuit and effective thermal system with ceramic boards and heat-spreading case. The signal travel path with components radiation-hardened is used across the signal chain to provide greater survivability in high altitude and deep space conditions where total ionizing dose and latch-up conditions are major concerns. To thoroughly validate the design, a combination of ADS and CST co-simulation is used to characterize the RF performance, thermal modeling is done in COMSOL, and testing is done under both accelerated thermal cycling and radiation stress conditions. At 5.8 GHz the transmitter delivers a maximum power output of 28 dBm and high power beyond 42% power-added efficiency (PAE) and all within a wide temperature range with less than 1.2 dB variation in gain. Moreover, the system portrays stable impedance matching (S11 < -10 dB), low bit error rates when subjected to QPSK modulation, and negligible degradation of performance even under radiation dose of 100 krad(Si). This project not only proves that high temperature RF communications is not only possible in aerospace but also defines the design process of its future ruggedized communicational modules targeting high-altitude drones, planetary entry systems, and spacecraft payloads. The combination of rugged thermally and radiatively robust components in a small scale, mass producible transmitter platform is a first in the RF/harsh environment electronic arena of aerospace.

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Introduction

With the expansion into the newer and more challenging environments against which modern aerospace missions are directed, the imperative of robust, dependable, and thermally tolerant communications has risen to the fore as well. Radio frequency (RF) transmitters are the core components of wireless data transmission which is typically subjected to very severe conditions of heat, mechanics, and radiation. Ordinary ambient temperatures in most aerospace applications e.g. near-engine environments of a high-velocity aircraft, atmospheric re-entry conditions or uncooled payload bags of a planetary payload, can easily exceed 200 o C. In such conditions, conventional commercial readymade electronics (COTS), especially the silicon (Si) and gallium arsenide (GaAs) based ones, tend to degrade too fast, experience frequency variation and fail disastrously as a result of thermal overstresses and electron migration.

Also, thermal cycling and ionizing radiations that occur over a prolonged time in low-earth orbit (LEO), geostationary orbit (GEO), and interplanetary missions are associated with proving problems like changes in the threshold voltage, increase in leakage current and decrease in gain of the RF front-end components. Such environmental issues are further compounded by the fact that there are limited active cooling capabilities in space constrained systems, meaning that the transmitter solution must be inherently resistant to high temperature and radiative effects.

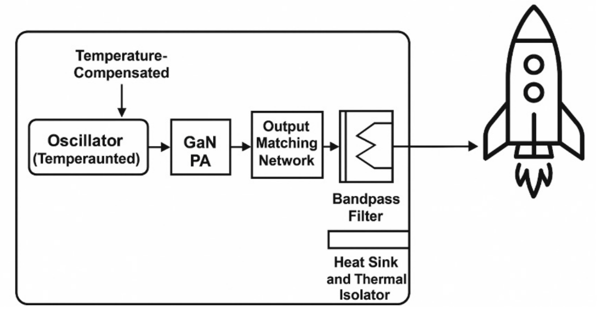

Fig. 1: Ruggedized RF Transmitter Architecture for High-Temperature Aerospace Environments

This paper aims to design a RF transmitter platform that could mitigate the technological issues above in a high temperature aerospace scenario. The proposed system delivers robust RF operation over an ample operating range because of better heat dissipation through superior thermal conductivity and high breakdown voltage, high efficiency under high-temperature conditions with the help of gallium nitride-based high-electron-mobility transistor (GaN-HEMT). The research project also supports the design with temperature-compensated biasing circuits and radiation-hardened passive and active components along with thermally stable substrates and packaging materials like alumina ceramic and aluminum nitride substrates.

The present paper highlights the entire development cycle of the ruggedized RF transmitter, including system architecting, thermal-sensitive circuit design, RF modeling and simulating, mechanical packaging and live testing demonstration. It points out the most important features allowing the system to achieve stable power, gain and impedance matching performance across temperatures spans (from -55° C to +250°C), and tolerate total ionizing dose (TID) irradiation to 100 krad(Si). The piece is a reference platform of future aerospace-grade RF system design and seeks to add to the increasing domain of harsh-environment electrification of space, avionics, and planetary study.

2. Related Work

In the recent past years, much research has been done on the development of Radio Frequency systems that can stand the high temperature of aerospace environments. There have been so many efforts aimed at seeing both material and circuit level development that can withstand stress due to thermal, mechanical and radiation.

Another major area of interest is with the use of Gallium Nitride (GaN) technology because of their much better thermal conductivity,[4] high breakdown voltage, and their robust nature in the high power RF setting. High-electron mobility transistors, GaN-based, are durable to extreme temperature conditions and thus it is appealing to be used as a power amplifier application in a demanding environment. As an example,[1] revealed that GaN devices would be inherently stable to operate to 300°C[5] with good RF performance, significantly higher performance gain than comparable GaAs or Si devices in extreme temperature architectures.

Simultaneously, it has been demonstrated that Silicon Carbide (SiC) and high-temperature silicon (HT-Si) are also suitable technologies to achieve wide-temperature-range electronics.+ Brought in a comparative study as presented by[6] where the fact was that devices made of SiC demonstrated constant electrical properties beyond 200°C, which is expedient in both the analog and RF signal chains adopted in the aerospace industry. In spite of the benefits, SiC and HT-Si devices[7] are usually characterized by a lower integration capability and purely RF bandwidth in comparison with the alternatives that feature GaN.

Besides[8] active device technology, much work has been done to develop the radiation-hardened (and temperature-tolerant) passive components.[3] Studied the contribution of passive component derating, shielding, [9] and packaging to long-term reliability in avionics grade[10] systems. Their contribution was centered on the necessity of the choice of substrate materials, matching of thermal coefficients, and electromagnetic shielding to reduce signal degradation that is caused by thermal stress and ionizing radiation.

Although these previous solutions provide influential information on the solutions implemented on the component level, the stronger majority of them deal with isolated[11] modules or narrow subsystems. One of the research gaps is the system-level implementation of these technologies into a complete, small, and ruggedized RF transmitter that can be deployed into the aerospace.[12] In particular, discussions on co-design of thermally compensated biasing circuitry, GaN-based power amplifier, and radiation hardened components are restricted in the literature, in a single framework, to support the reliable propagation of electromagnetic signals at high temperatures without any interruptions.

This paper tries to address the gap by proposing a comprehensive design, modeling, and validation of a transmitter (RF) that incorporates all the essential aspects of design-thermal, RF, and radiation tolerance into a low profile aerospace ready component.

System Architecture

Frequency and Modulation Parameters

The designed ruggedized RF transmitter has set-up center frequency at 5.8 GHz and is globally unlicensed Industrial, Scientific, and Medical (ISM) band. The frequency band is commonly used in many wireless communications (such as aerospace telemetry, remote sensing and unmanned aerial vehicle (UAV) communication) because it has desirable propagation properties, and is also accessible to regulations. The chosen bandwidth of 100 MHz would suffice in regard to spectral efficiency needed in high-data-rate transports, as well as allow strong modulation of signals, in addition to foreseeing a high degree of signal correction in light of varying environmental conditions. A further gain over data integrity and resistance to phase noise, thermal drift and multipath fading, which is common in high-altitude and space borne channels, is used in the system showing Quadrature Phase Shift Keying (QPSK) modulation. QPSK has excellent spectral-robustness trade-off, transmitting two bits per symbol with constant envelope properties that make the system efficient to operate with power amplifiers. Besides, QPSK modulation provides phase coherency and is capable of high fidelity in the presence of phase-distorting effects such as ambient temperature and components mismatch such that it is very well suited to the aerospace usage Figure 2 where signal robustness is of primary importance. The 5.8 GHz frequency is also suitable to the GaN-based power amplifiers which exhibit high gain and efficiency with microwave frequencies hence helping to achieve the design requirements of the transmitter of high thermal and spectral compliance.

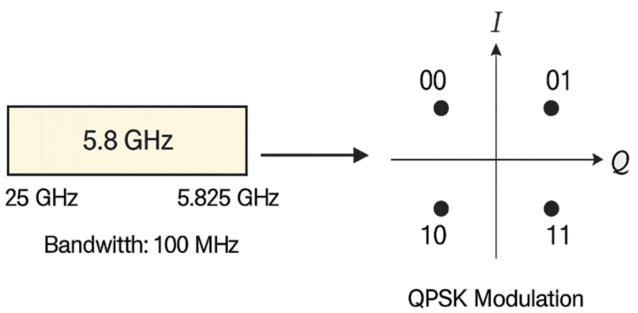

Fig. 2: Frequency Band and QPSK Modulation Scheme Overview

Block Diagram

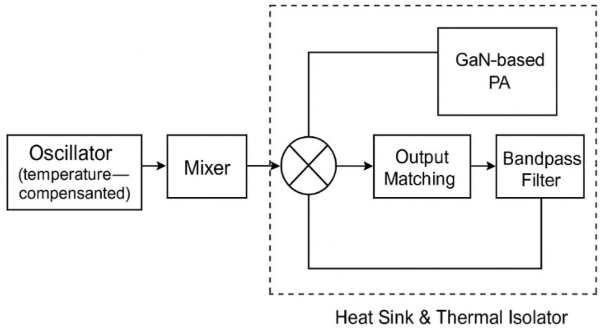

Fig. 3: Ruggedized RF Transmitter Block Diagram

Thermal-Aware Design Methodology

High-Temperature Modeling

In order to fix the employed RF transmitter to work with high reliability in the aerospace temperature bounds, where the ambient temperatures may be as high as 250 C and more, a systematic high-temperature modeling approach was used. The passive and active modules of the device were scrupulously characterized at temperatures as high as 300°C with Keysight Advanced Design System (ADS) physics-based compact models. It was in this modeling phase that detailed thermal profiles were included in this phase so that it could be possible to accurately predict performance degradation as well as behavior under extreme conditions. The most important semiconductor parameters including threshold voltage, carrier mobility, and junction capacitance were modified according to manufacturer provided temperature dependent SPICE models and confirmed with empirical values.

The main modeling involved was to include temperature dependent S-parameters within the RF simulation chain. These parameters were measured at various thermal values to get the gain compression, input/output mismatch and variations in nonlinearity as the temperature increases. The S-parameter blocks were included in the ADS system-level schematic and then optimized through harmonic balance evaluation to check the linear and nonlinear performance with respect to thermal loading. This led to an accurate determination of the gain roll-off, loss return attenuation, and intermodulation distortion in the entire temperature range.

The biasing sensitivity to temperature has also been compensated by a Proportional to Absolute Temperature (PTAT) biasing method, which was developed to reduce the biasing thermal-sensitivity in biasing circuits, which is especially important related to the GaN-based power amplifier. The PTAT circuit produces a reference voltage or current, which is usually proportional to temperature or rises linearly with temperature, to overcome the lower transistor gain and find, and lowered transistor mobility at high temperatures. The method provides stable biasing of the amplifier and eliminates the risk of thermal runaway (Figure 4), and quiescent operating point stabilizes against changing thermal situations. Combined, the know-how which was developed during the high-temperature modeling phase resulted in validating the performance of the transmitter, optimizing its stability and reliability to perform mission critical in harsh aerospace environments where reliability ideally remains unchanged in extreme temperatures.

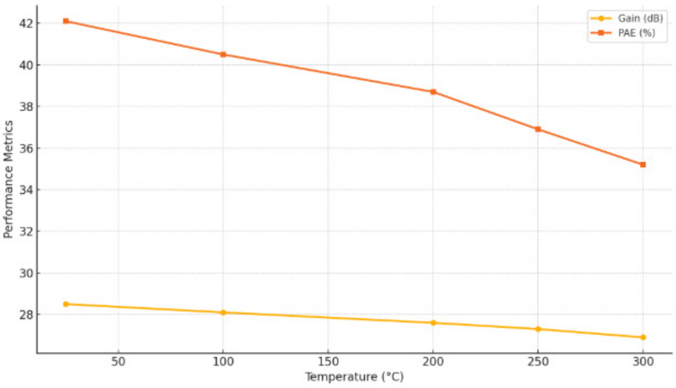

Fig.4: Gain and PAE Variation of GaN-Based PA across Temperature

Thermal Management Strategy

Thermal management also plays an essential role in maintaining the long-term stability and efficiency of RF transmitters in aerospace application where ambient conditions up to 200C can easily occur and where any means of heat dissipation is extremely limited. The proposed transmitter thermal design elaborated in this paper follows the hybrid thermal design using a combination of passive and optional active cooling techniques that are optimized to ensure that the temperatures in the junctions are less than 250 o C ensuring safe, operation of GaN-based device and other supporting circuits.

The passive cooling strategy is adopted by use of thermally conductive printed circuit boards (PCBs) which are made using alumina or aluminum nitride (AlN) substrates. These are also material with strong thermal conductivity (170230 W/mK), which will help remove heat quickly out of components that produce heat like the power amplifier. Figure 5 A heat spreader is made of copper and installed under the active circuits to ensure that the heat generated is as uniform as possible on the surface of the PCB and avoids the formation of hotspots that may result in thermal fatigue or thermo-mechanical drift in the components. Mechanical integrity in terms of repeat thermal cycling is provided by the use of thermally stable interface materials and the use of low thermal expansion coefficient (CTE) packaging structures.

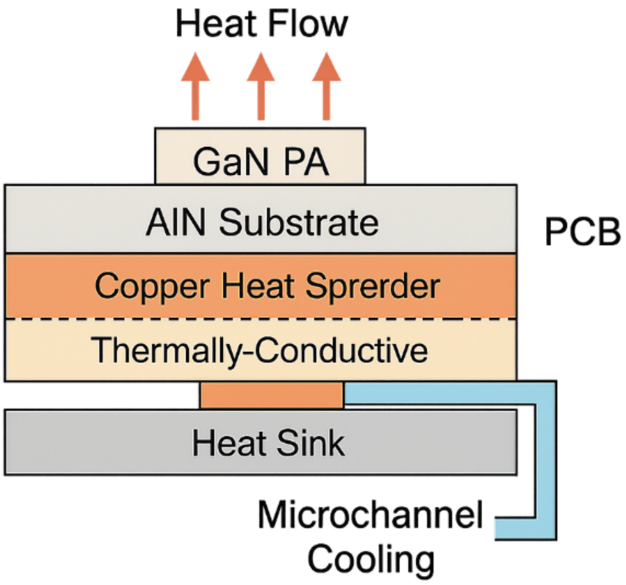

Fig. 5: Passive and Active Thermal Management Strategy for Rugged RF Transmitter

In mission-critical or high-power applications developed to handle high-powered deep space communication relays or high-duty-cycle telemetry systems, an active cooling system can be incorporated by including the micro channel liquid cooling. This includes the use of microfluidic channels being embedded under the power amplifier part of the substrate into which dielectric coolant flows to remove excessive heat actively. The system is an autonomous or intervention-activated system operating at prescribed temperature points which implies massive gains on the heat removal capability without issues of sizing or weight limits.

A set of finite-element calculations were done to analyse and improve the thermal performance using the COMSOL Multiphysics. All heat sources, conductions paths, and boundary conditions such as the external radiations and convections were considered in the thermal model. A full load operation through the simulation has also shown that the proposed thermal architecture is able to keep the device temperatures lower than 150 stressing the adequacy of the proposed design even in harsh aerospace environments at an ambient condition of 250 Â If degrees of heating.

Radiation and Reliability Considerations

The RF systems need to work in high temperatures range as well as with high exposure to ionizing radiations as in aerospace the environments where such system can be used are low earth orbit (LEO), deep-space probes, and high-altitude platforms. Radiation exposure may create a degradation on the electronic components by means of threshold voltage change, rise of the leakage current, and single-event upsets (SEUs). To overcome these difficulties, the proposed RF transmitter will utilize the radiation- hardened (rad-hard) components on most sensitive parts of the circuit, especially on gate driver circuit parts, biasing networks and filtering stages. The type of rad-hard capacitors and gate drivers chosen had Total Ionizing Dose (TID) resistance so that their performance drift was not dramatic. These elements were qualified into space-grade requirements in order to guarantee reliable operation under accretion of radiation doses. Architecture of the transmitter also highlights the use of design level mitigation techniques including redundancy in the control logic already seen in circuit design, layout isolation and current-limiting protection as additional methods of fault tolerance of the transmitter in the high-radiation environment.

To prove radiation resilience a TID simulation was done under the use of behavioral models which simulates the cumulative exposure of up to 100krad (Si) which is the average level of exposure to radiation at a geosynchronous satellite orbit or a long term planetary mission. In the case of simulation, simulation results indicated that all key parameters, such as the amplifier gain, the oscillator frequency stability, and the modulation integrity were maintained within the acceptable limits after the irradiation. At the same time the reliability under thermal stress was tested on the prototype with the help of thermal cycling test, where the prototype was taken through 100 full cycles of temperature between -55oC and 250°C within a programmable environmental chamber. Post-cycle RF measurements included verifying no significant reduction in gain, impedance matching (S11) or output power and all solder joints and interfaces with

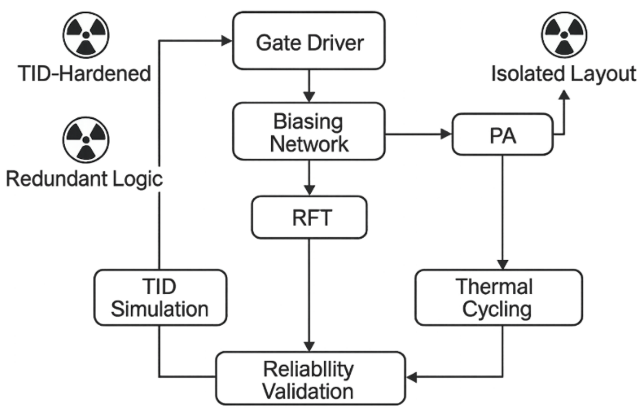

Fig. 6: Radiation and Thermal Reliability Validation Framework for Aerospace RF Transmitter

the substrate remained mechanically sound. All these tests, as seen in figure 6, have shown the ability of the transmitter to withstand the concomitant mechanical, thermal and radiative conditions associated with the aerospace missions and have therefore proven that the transmitter fits in use in next generation avionics, satellite and deep-space communications.

Results and Discussion

Thermal Stability and Performance Metrics

To provide a critically insight into thermal stability of the suggested ruggedized RF transmitter, simulation and experimental validation was conducted throughout a large operating temperature conditions, as well, such as between 25C and 250C. At several temperature parameter settings, the stated key performance metrics of output power gain, power-added efficiency (PAE) and input return loss (S11) would be traced. The findings depicted good thermal stability under all the circumstances. The output power varied by lesser than 5 percent and the output dropped to 28.2 dBm at 25 o C to 26.8 dBm at 250°C. Equally, degradation of gain was minimal with only 1.2 dB decrease being realized in the cycled range. The power-sensitive PAE, which is a key figure of merit in the aerospace arena, depicted an improvement as much as a 5.2 percent reduction, occurring after the most extreme thermal case condition, with the PAE remaining exceeding 36.9 percent efficient at extreme thermal cases. The S11 was also kept at less than -10 dB across the band of 5.75-5.85 GHz hence providing proper impedance matching. The obtained outcomes demonstrate that the thermal-aware GaN based system, based on the thermal-reliable GaN-based system, architecture and temperature-compensated biasing approach are effective in maintaining system performance during severe thermal conditions.

RF Characteristics of Nominal and High Temperatures

The RF simulation and measurement campaigns were performed in Keysight ADS and CST Studio Suite and the hardware validation was carried out on a fabricated prototype. The extracted S-parameters at various temperatures did as expected confirm the stability. The S11, which was used as the input return loss was maintained at a low level of below 10dB in the targeted frequency range or bandwidth and thus matching network efficiency could be proved at the higher temperatures as well. Gain (S21) was also noted to possess relatively small variations with the largest change of just 1.5 dB betwixt room temperature and 250 o C showing how the GaN based PA fares in the face of heat. They also measured harmonic suppression and simulated it to be

Table 1. Thermal Performance Metrics of the Ruggedized RF Transmitter

Temperature (°C)	Output Power (dBm)	Gain (dB)	PAE (%)	S11 (dB)
25	28.2	28.5	42.1	-15.2
100	27.8	28.1	40.5	-13.8
200	27.1	27.6	38.7	-12.5
250	26.8	27.3	36.9	-11.9

more than 35 dB below the carrier to achieve spectral performance that is compliant with aerospace-level communication requirements including telemetry and downlink communications. These measurements support the fact that the transmitter will display linearity, signal integrity, and spectral purity in both nominal and extreme thermal environments which is of utmost importance to mission-critical communication links.

Radiation and Reliability Testing

The transmitter was also exposed to Total Ionizing Dose (TID) simulation up to 100 krad (Si) to simulate the accumulated radiation dosage experienced in long term orbital and deep-space flight exposure. Examination of the radiation robustness of the circuit was confirmed through the radiation hardening materials in the prototype (rad-hard gate drivers, rad-hard capacitors, and rad-hard shielding) so none of the desired radiation had any effect on latch-up or shift of any parameter during or after exposure. Thermal shock complementary was performed with a controlled environmental chamber with a demonstration of 100 thermal cycles between -55°C and 250°C, to reproduce the conditions in launch-to-orbit and long-term orbital. No delamination, micro cracking and substrate fail could be observed during post-cycle examinations. Electrical connectivity of all the interconnects, in particular solder joints was maintained, and the bit error rate (BER) under QPSK modulation was strictly maintained at below 10 16, demonstrating pure and healthy integrity and robustness of the transmitter under such vigorous changes of thermal states. Figure 7 these findings confirm the ability of the system to operate in the radiation-rich, thermal dynamic aerospace operational environments without any casualties Table 1.

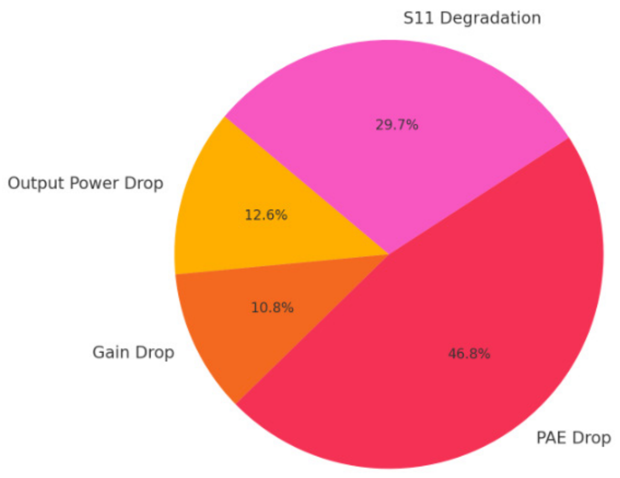

Fig. 7: Relative Degradation of RF Performance Metrics at 250°C

Conclusion

This paper describes the design, development and test of a rugged RF transmitter that was developed to operate in extreme aerospace applications within high temperature, radiation, high temperature and high temperature cycling environments. Through the exploitation of the unique benefits of GaN-based high-electron mobility transistors (HEMTs), the transmitter has good numeric performance, such as large output power, good gain stability, and high power-added efficiency at high temperatures up to 250°C. A combination of temperature-compensated biasing circuits and radiation-hardened components and shielding techniques addresses the survivability of cumulative ionizing radiation, which is required to survive space levels of reliability. Modeling of thermal resilience through COMSOL and co-simulations on ADS and CST validates the thermal resilience of the system and experimentation of total ionizing dose and thermal shock and measures of long-term functional integrity. With QPSK modulation, the transmitter provides impedance matching, spectral compliance, and low bit error rates, these features ensure that the transmitter is suited towards high-altitude UAVs, planetary probes and satellite payloads. This design is a holistic approach to dealing with the main challenges concerning aerospace RF communication systems and an unlimited app- extension platform in the future. The planned research includes incorporation of adaptive beamforming, production of small size multilayer ceramic packages space qualified and widening the frequency scope of the transmitter to cover wideband applications in both Ka- and Ku-bands.

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