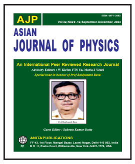

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Development of an X-band microwave power module for airborne radar

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Dedicated to Prof B N Basu

A narrow band microwave power module (MPM) operating in X-band was developed that delivers 175W of peak output power with 52.5 dB nominal gain up to 20% duty cycle of operation. This MPM has a solid-state power amplifier (SSPA) as the driver amplifier followed by a power booster mini-travelling wave tube (mini-TWT) for achieving superior efficiency and noise performances. The MPM is packaged in an aluminium enclosure within a volume of 270 mm × 240 mm ×110 mm and weighs about 6.3 kg. The enclosure is openable in two halves to maximize the surface area available for accommodating the RF Section and the Electronic Power Conditioner (EPC). This concept of two-halves configuration enables the MPM operation without any cooling mechanism for a duration lasting up to 5 minutes. The compact electronic power conditioner incorporates high frequency switched series resonant power converter for catering the high voltage requirements of the mini-TWT. The high voltage section has a planar transformer for achieving superior efficiency and high power conversion density. The RF Section consists of both passive and active components which delivers the required output power and provides a sample signal for both protection and power monitoring purposes. The TWT used in the RF chain consists of Pierce-type electron gun, negatively dispersive slow wave structure (SWS), single stage depressed collector, and periodic permanent magnet (PPM) focusing structure to obtain required overall efficiency of 35%. The MPM successfully underwent stringent environmental tests and the EMI/EMC specifications as part of the qualification tests.

Keywords: RF Transmitters, Microwave Power Module (MPM), Electronic Power Conditioner (EPC), Travelling wave tube (TWT), Slow-wave structure (SWS), Depressed collector, PPM focusing, Electron gun.

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1 Introduction

A compact microwave power module (MPM) is one of the critical subsystems of an airborne radar that consumes a lion’s share of the prime power, occupying significant volume and weight. The challenging requirements in size, weight and power (SWaP) with increased functionality and performance makes the transmitter technology very critical for the overall system engineering. This article brings out the development efforts made in meeting these challenging requirements by using a microwave power module (MPM), for achieving high SWaP index and reliability. The high-level configuration of the MPM is as shown Fig 1. The MPM is packaged in two halves in order to maximize the surface area for spreading heat for the intended transient operation without cooling. The bottom-half, which is called the RF section, consists of a travelling-wave tube (TWT), a solid state power amplifier (SSPA) and a set of RF components for the protection and power monitoring purposes. The top-half consists of the electronic power conditioner (EPC) that generates the voltages required for the operation of the RF section and logic circuits for protection purposes.

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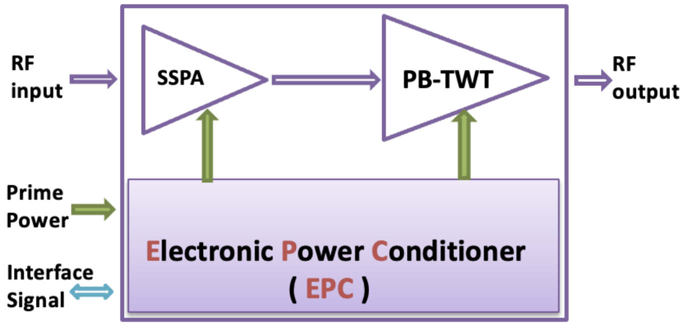

Fig 1. Block diagram of the MPM

2 Electronic power conditioner

The electronic power conditioner (EPC) comprises multiple high density custom-developed high voltage and low voltage DC-DC converters configured for powering various electrodes of a TWT with built-in sequencing, fault monitoring and protection mechanisms besides a remote control interface [3-4]. It is constituted with five major sections, namely,

- EMI Filter Section,
- Housekeeping Power Section,
- Heater and BFE Modulator Section,
- High Voltage Cathode Converter Section, and
- Embedded Interface and Control Logic.

The top level block schematic and assembly of the EPC is as shown in the Fig 2.

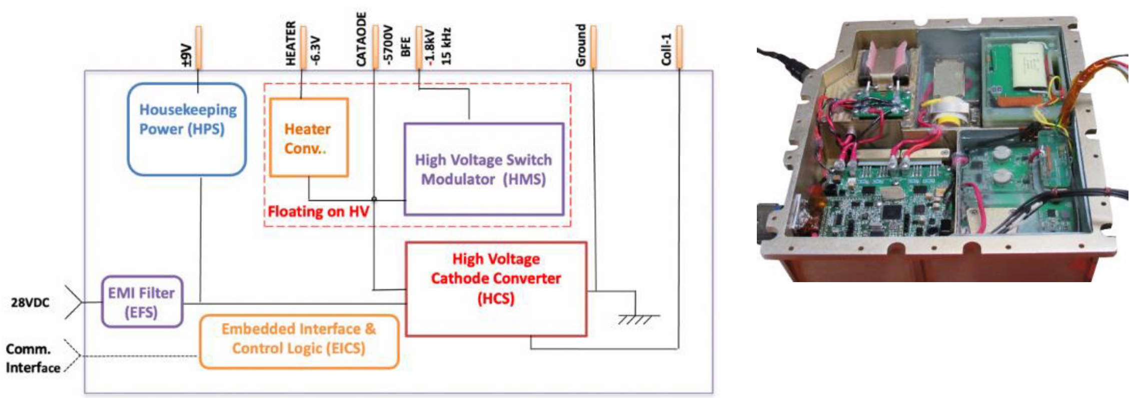

Fig 2. Block diagram and EPC module assembly of the electronic power conditioner.

A. EMI Filter section

The EMI filter section attenuates the incoming voltage transients and EMI on the prime power bus of the EPC. It also prevents the electromagnetic interference generated by the high frequency switching converters and fast modulator in the EPC from propagating back along the prime power bus (that may otherwise interfere with other subsystems). The EMI filter is constituted with two differential-mode (DM) and one common-mode (CM) filters apart from two feed through pi-filters. The cut-off frequencies of the filter sections are decided based on the ripple frequency measurements done on the cathode-collector power converter under the full resistive load condition. The filter stages are compartmentalized for ensuring best isolation between the successive filter stages. The interconnections are carried out through slots made on the separating walls between the filter sections. .

B. Housekeeping power section

The housekeeping power section caters the entire internal low voltage power supply requirements and the SSPA power requirement. This section has been developed based on off-the shelf DC-DC modules with an additional sensor circuit for monitoring and protection. Each of the power converters is decoupled using low ESR capacitors close to the power pins and protection fuses. Separate local power filters are incorporated each of the modules in order to reduce the emission from these modules.

C. Heater & BFE modulator section

This module caters the power required for the heater and bias electrodes. This is based on half bridge topology with voltage multiplier network for generating the 1.8 kV bias voltage. Considering the noise sensitivity of the heater power supply, it is post regulated using linear regulator with current fold-back mechanism for protecting the TWT at the cold start. This section has an integrated semiconductor high voltage switch for modulating the bias electrode from 1.8 kV to 0 V at 20 kHz PRF up to 20% duty cycle of operation. The circuit consists of two high voltage MOSFETs in totem-pole configuration, with the midpoint for the BFE control. Two complementary signals are generated by an advanced digital algorithm fused inside the CPLD for ensuring OFF before ON operation of the high voltage switches with suitable delays in between. These two complementary signals are transported to the MOSFET driver by using pulse transformer to provide the desired isolation of 10 kV.

D. High voltage cathode converter section

This section caters the high voltage requirements for the cathode/collector electrodes of TWT. However, at all the electrodes, the voltage ripples contribute to the noise of the MPM. The contribution due to the cathode electrode is considered to be the highest. For achieving stringent specification of the voltage ripple, a full bridge phase-modulated series resonant converter (PM-SRC) topology is selected. The PM-SRC operates at a constant switching frequency with duty ratio control for achieving the regulation in the output. The fixed switching frequency of the PM-SRC is an advantage over the variable switching frequency operation of the classical SRC. Conduction of switches on the leading leg of the inverter is phase-shifted suitably with respect to the conduction of switches on the lagging leg in order to obtain a quasi-square excitation voltage. The variable width of the excitation voltage (duty ratio, D) controls the power delivered. Parasitic inductance of the transformer, which limits power flow, becomes part of the resonant inductance (L_r). The effective impedance offered by the parasitic inductance to power flow is reduced by including the resonant capacitor (C_r), and operating the converter near the resonant frequency (given by $1/(L_rC_r)$. The negative effect of the transformer parasitic capacitance is masked from the inverter by the resonant inductor. The resonant frequency of the tank is chosen to be below the switching frequency to operate tank current in lagging mode to achieve zero voltage switching (ZVS). This topology also enhances the converter efficiency. For increasing the converter power density, the power converter bridge is switched at 200 kHz. After this, a hybrid-tripler is employed to generate the required high voltages for cathode and collector electrode.

E. Embedded interface and control section

The embedded interface and control section is responsible for the control, remote interface, power sequencing, monitoring, and protection of all the sub-sections of the transmitter.This is a real time embedded control module based on microcontroller and CPLD. A detailed analysis is carried out and the various tasks are evolved for this section. Low response and flexible tasks are implemented into software and high priority and low latency tasks are implemented in hardware. It embeds intelligence into the system improving the system performance and reliability.

3 Travelling wave tube

An indigenously designed and developed mini-Helix-TWT is used in the MPM as a power booster amplifier which delivers a minimum RF output power of 250 W across the operating frequency band. The TWT consist of five subassemblies, namely, an electron gun that emits high velocity electrons; a slow-wave structure (SWS); periodic permanent magnet focusing structure that confines the electron beam along the SWS; depressed collector for recovering electron energy partially to enhance overall efficiency; and RF couplers to feed in input and take out RF signals [5-6].

The TWT uses Pierce-type electron gun that operates at cathode voltage of around 5600-5700 V to emit the electron beam from an M-type cathode that operates at a current density of around 4 A/cm^2. The emitted electron beam is controlled using beam focusing electrode (BFE) to reduce the diameter and to increase the current density of the electron beam to around 15 A/cm^2 before entering the SWS. The BFE is also used to pulse the electron beam. The TWT uses a focusing structure based on periodic permanent magnet (PPM) that consists of high energy density and thermally stable Samarium Cobalt (Sm_2Co_{17}) magnets. The designed peak magnetic field of the PPM is around 2600 Gauss. This TWT uses a negatively dispersive SWS that consist of helix supported by three anisotropic pyrolytic boron nitride (APBN) dielectric support rods and metallic vanes. These three dielectric rods are placed at 1200 apart azimuthally around the helix and provide electrical insulation and thermal dissipation path for the helix. The metallic vanes are used to control the dispersion and interaction impedance characteristics of the SWS [7]. The designed length of the SWS is around 93 mm with a basic electron efficiency of 20%. A single stage depressed collector that operates at 45% of cathode voltage is used for enhancing the overall efficiency of the TWT to 35%. The shaping of the collector electrode is designed such that the electrons land smoothly on the electrode. The smooth landing of electrons at the collector facilitates improvement in the thermal management and reduction in the emission of the secondary electrons. Reactive impedance matching technique is used for matching the characteristic impedance of the SWS (which is around 100-110 ohms) to standard SMA (f) and TNC(f) at the input and output connectors of the TWT, respectively. This approach could provide VSWR less than 1.8:1 for both the input and the output connectors. The baseplate, which is made of Al-6061, is designed in such a way that the TWT can handle the thermal dissipation up to 5 minutes without any cooling.

Fig 3. Developed prototype TWT.

The packaging of the TWT is critical in that it should withstand the thermal and mechanical stresses during the operation on airborne radar systems. The high voltage portion of the TWT is encapsulated with RTV based silicone potting compound which provides electrical insulation and structural support. The SWS region is encapsulated with a mixture of aluminium fillets and low viscosity epoxy resin to provide better thermal path and structural rigidity. The collector top cover is nickel plated to prevent the surface oxidation at elevated temperature of operation.

Prototype TWTs are indigenously developed at M/s Bharat Electronics Limited (BEL), Bangalore, which delivered a minimum peak RF power of 250 W, with overall efficiency of 35% (minimum) throughout the operating frequency band. A developed prototype TWT operating at cathode voltage of 5600 V is shown in Fig 3 [7]. The measured power and gain plots of a prototype TWT are shown in Fig 4. The measured electronic and overall efficiencies of a prototype TWT are shown in Fig 5. The weight of the developed TWT is around 700 g.

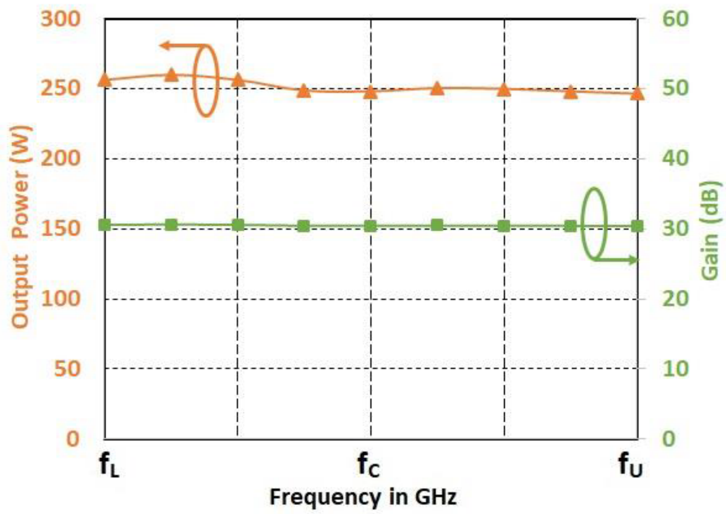

Fig 4. Measured performance of prototype TWT.

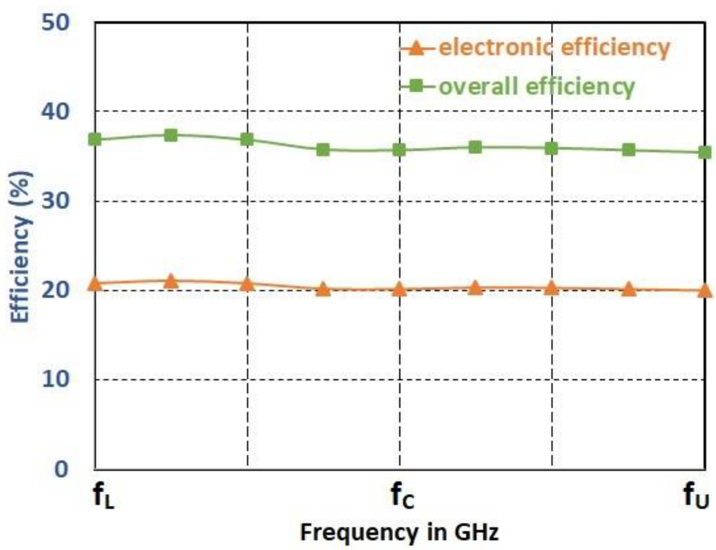

Fig 5. Measured electronic and overall efficiency of prototype TWTs.

4 RF section of the MPM

The basic RF requirement of the MPM is to provide a minimum output power of 175 W over input drive variation of 0 ±2 dBm. The R F Section also requires a sampled output signal for monitoring the output power during integration with radar sub-systems, another sampled output signal for monitoring the operational safety of the TWT internally by EPC, and a VSWR protection circuit against load-mismatch at the output of the MPM. Apart from these requirements, we have to consider the gain variation across various TWTs.

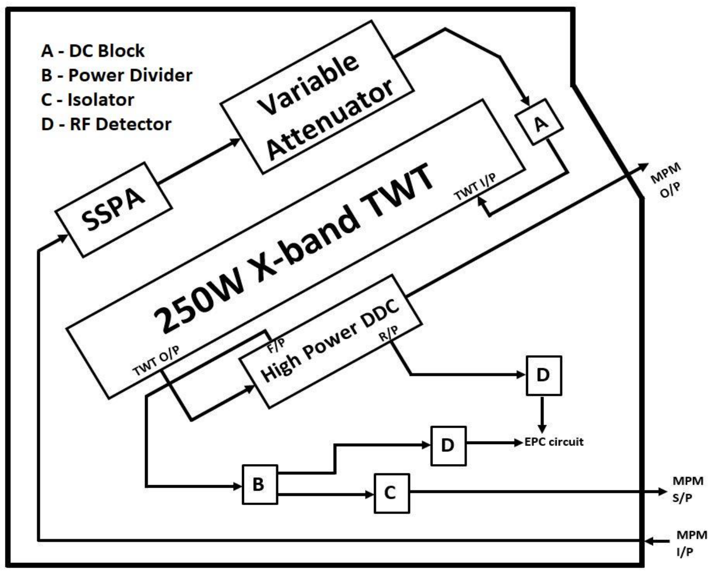

Fig 6. RF section block diagram.

The RF chain is designed to meet the above requirements. A typical block diagram of the RF chain is shown in Fig 6. The RF input of the MPM is fed to SSPA using a semi rigid cable assembly which has a loss of around 0.5 dB. The SSPA is designed such that it provides a saturated output power for an input power of –2.5 dBm to +1.5 dBm. The constant output power of the SSPA is given to TWT through a variable attenuator and DC block. The variable attenuator is used to adjust the RF signal strength required to drive the TWT. The DC block is used to protect the SSPA from the DC currents that may flow from the TWT through the RF centre conductor of its input connector. The output of the TWT is connected to Dual Directional Coupler (DDC) using 90^{o} bend adapter. The forward sampled signal (F/P) of the DDC is fed to 3 dB power divider: one output port of the power divider is connected to a zero bias schottky detector and the detector output is fed to EPC for monitoring the TWT health internally; whereas the other output port of the power divider is connected to the sampled port of the MPM through an isolator. The isolator is used to avoid the unbalancing of the power divider due to load-mismatch at the sampled port of the MPM. The reverse sampled signal (R/P) of the DDC is fed to zero bias schottky detector, which is fed to EPC logic circuit for VSWR protection. In the event of the load VSWR crossing the tolerable limit or the output power falling below the minimum power, the high voltages to the TWT will be switched off, by the control logic. This protection circuit saves the TWT from any irreversible damage due to load-mismatch at the output of the MPM and high voltage failures inside the EPC. The output of the DDC is connected to the MPM chassis using a high power flexible cable. The high power RF path is designed with minimal interconnections to reduce the insertion loss.

The specifications of all the active and passive components are derived to match them with Commercially off the Shelf (COTS) components except for the TWT. All the low RF power interconnections are made using semi-rigid cable assemblies. A prototype R F section is integrated and tested with universal TWT power supply, which delivered a minimum power of 210 W. The RF section is fully qualified for airborne system specifications. A typical prototype RF section performance against the input drive power at ambient conditions is shown in Fig 7.

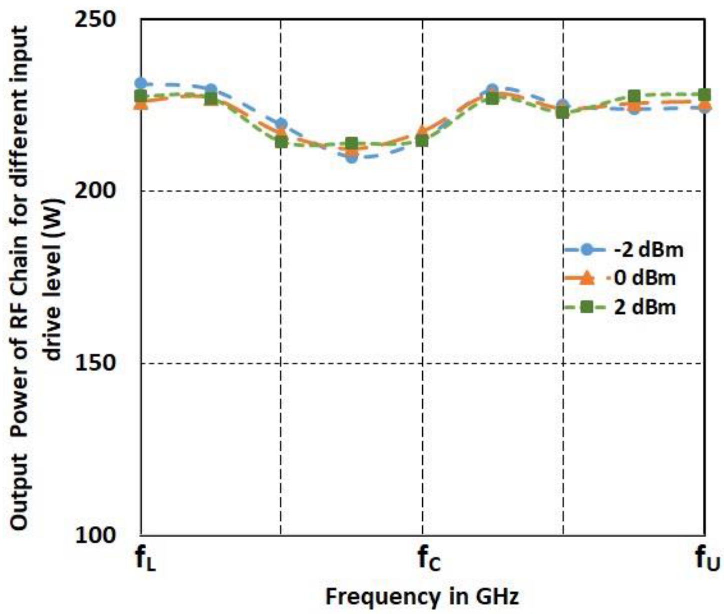

Fig 7. Performance of prototype R F section.

5 Results and Discussion

A prototype MPM is integrated with the indigenously developed EPC and RF section as shown in Fig 8. The MPM is tested for different DC bus-voltages (like 24V, 28V, 32V), and delivered a minimum peak output power of 210 W throughout the operating frequency band. The peak output power and 28V DC bus power consumption at duty cycle of 20% for a prototype MPM are shown in Fig 9. The measured rise time and fall time of the pulsed RF output is less than 45 ns and the corresponding plots are shown in Fig 10. The measured spurious and second harmonics of the RF output are better than –55 dBc and -18 dBc, respectively. The corresponding spurious and harmonic plots at a centre frequency for a prototype MPM are shown in Fig 11 and Fig 12, respectively. The measured additive phase noise is less than 2 dB with respect to input spectrum. The single side phase noise plots of input and output RF signal at centre frequency at 100 Hz away are shown in Fig 13 and Fig 14, respectively. The weight of the MPM is around 6.3 kg.

Fig 8. Developed prototype MPM.

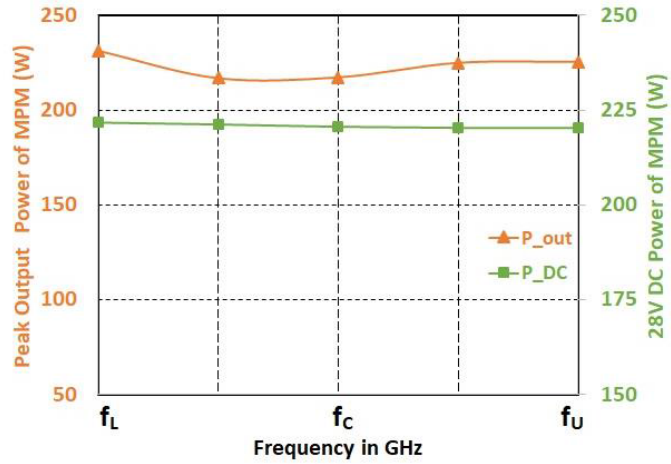

Fig 9. Output power performance of the prototype MPM.

Fig 10. Rise and fall time of the prototype MPM.

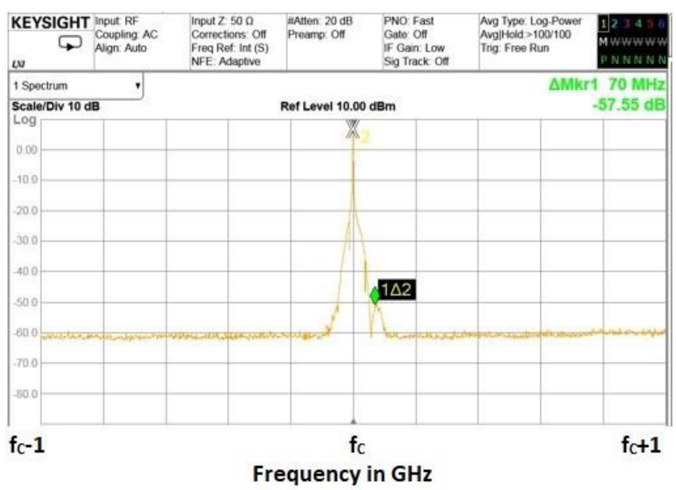

Fig 11. Spurious levels of the prototype MPM.

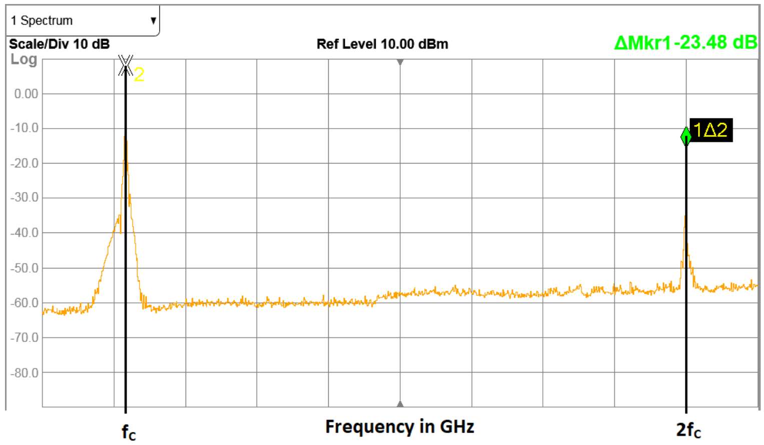

Fig 12. Harmonics of the prototype MPM.

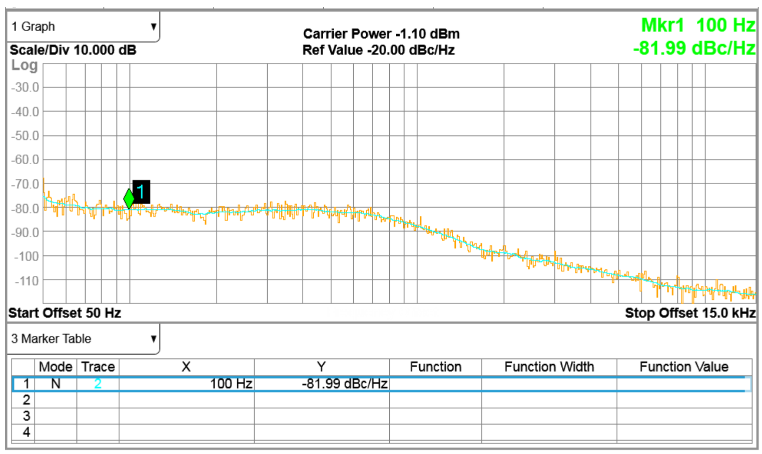

Fig 13. Input phase noise of the prototype MPM.

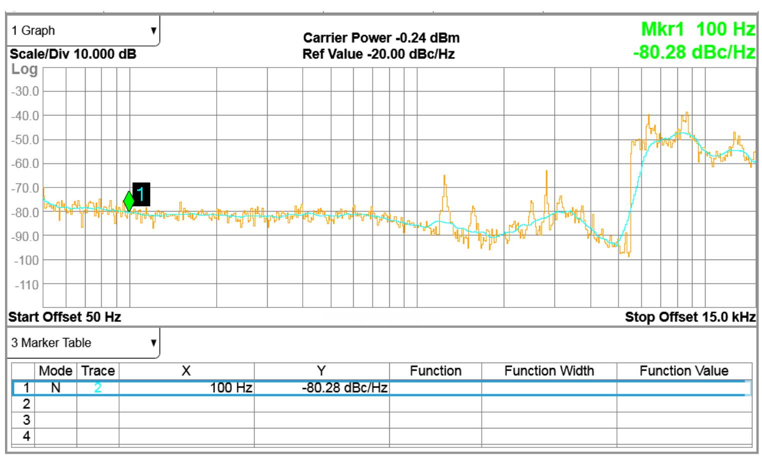

Fig 14. Output phase noise of the prototype MPM.

The MPM has undergone the environmental qualification like EMI/EMC, thermal cycling, low temperature test, high temperature test, random vibration, sinusoidal vibration, shock, acoustic, transportation test, long term climatic test, as per airborne system specification, and passed successfully. The MPM delivered a minimum output power of 200W under all the operating environmental conditions. The RF output power and 28V DC power consumption at 20% duty cycle, at the centre frequency, under various environment temperature conditions are listed in Table 1.

Table 1. Performance of prototype MPM under various temperatures

Test Conditions	Performance Results at centre frequency		
	Peak RF Output power	Average RF Output power at 20% duty	28V DC power consumption at 20% duty
Ambient room	217 W	43.4 W	221 W
Burn-in (50 °C)	212 W	42.4 W	220 W
Thermal Cycling(–20 °C)	222 W	44.4 W	229 W
Thermal Cycling (65 °C)	210 W	42.0 W	220 W

6 Conclusion

An X-band high power pulsed MPM has been designed, developed and has been qualified for airborne platform. Minimum peak output power of 200 W could be achieved with harmonics better than –18 dBc, spurious better than –55 dBc, and additive phase noise of less than 2 dB throughout the operating frequency band. The same performance could be ascertained under all operating environmental conditions and DC bus-voltages. The MPM weighed about 6.3 kg and the prime power consumption was less than 230 W for 20% duty cycle of operation.

Acknowledgment

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