Design of a High Power Solid State Amplifier to replace TWTAs in Airborne Applications

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This paper describes the amplifier design requirements for an airborne Electronic Counter Measures (ECM) application, and the solid state solution successfully provided by Milmega.

Milmega was founded in 1987 to design and manufacture RF and microwave power amplifiers and related systems. Initially technologies used include GaAs, silicon bipolar transistors, silicon FETs and microwave tubes. In recent years microwave tubes have been dropped from the range, as the company focused on developing its solid state expertise. Products range from simple amplifiers to complete systems, and many designs are to customer specifications.

Milmega products have won a number of national awards, including the UK Government "SMART" Award for the development of the octave band solid state amplifiers. The company operates from a purpose built factory in Ryde, Isle of Wight.

As a result of its earlier interest in microwave tube amplifiers Milmega received a requirement specification for a Travelling Wave Tube Amplifier, (TWTA), for an airborne ECM application. The basic requirements of the amplifier are summarized in Table 1.

An initial investigation by the design team suggested that a Gallium Arsenide Field Effect Transistor (GaAs FET) solution would be a practical alternative to the TWTA approach. This approach afforded reliability levels that superceded the customer expectations.

Milmega's proposed solid state solution was based on one of the company's standard products, a 3U 19" rack mounted 250W 1 to 2 GHz solid state power amplifier (SSPA), figure 1. The family of amplifiers on which the proposal was based was the outcome of a UK Government funded program which started in 1992 and enabled Milmega to develop rugged octave band amplifiers, initially intended for electronic warfare and EMC testing applications. The program objectives were to develop a range of 1 - 2GHz and 2 - 4GHz amplifier and power combiner modules which could be configured into amplifier systems delivering up to 200W or 400W CW at lower cost and with higher reliability than a TWTA.

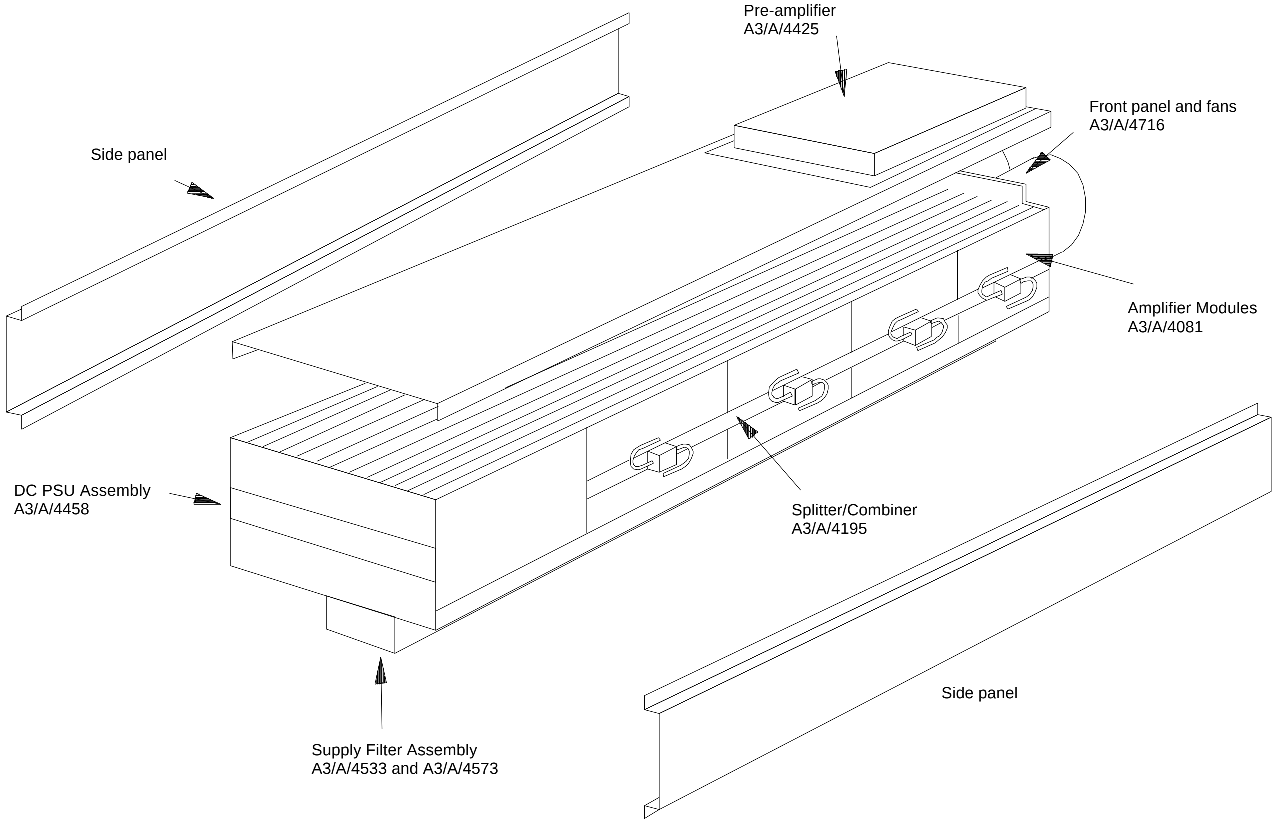
Table 1. Basic Amplifier Requirements

Parameter	**Requirement**
Frequency Range	850 to 1400 MHz
Saturated Output Power	250 W min.
RF Input Power (for Psat)	24 dBm (250mW) min.
Duty cycle	0 to 100 %
VSWR Input	2:1 maximum
Load VSWR tolerance	Operation into 1.5:1, survival any positive load, any phase
Harmonics	2nd –6 dBc 3rd –30 dBc
Spurious	-30 dBc
Noise level	+23 dBm total power measured in a wide band power sensor (>10 GHz).
Prime Power	115 vac, 3 phase, 400 Hz.
Power Consumption	2 kW max.
Environment	Pod mounted airborne

Figure 1. AS0102-250R Milmega Standard 1-2 GHz 250W amplifier

The main advantages of a solid state solution for this particular requirement could be summarised as;

- Improved Reliability
- Superior inherent VSWR/Load Tolerance
- Lower Power Consumption
- Lower Maintenance Costs
- Lower Harmonic and Spurious levels



In addition solid state offered benefits such as;

- ♦ Improved Power/Gain flatness
- ♦ No warm up time/ fast standby
- ♦ Lower Noise Figure

The solution that was proposed, and accepted by the customer, required the mechanical redesign of the commercial modules, the combiner divider, and the design of new power supply unit. The outline of the proposal is shown in figure 2.

Figure 2 Basic Construction of Pod Mounted 250W amplifier

The Design Approach

The main challenge with the design came in terms of the mechanical arrangements. The volume available was less than the commercial product offering, the shape was completely different (750 x 170 x 200 mm), the operating temperature higher, and the unit had to work at an altitude of 40,000 feet. Getting the thermal design right was going to be key to achieving the reliability requirements.

The RF input is applied to the driver amplifier module, a class A GaAs FET amplifier, having an output of 8W over the 850MHz to 1400MHz band. This is fed to an eight-way solid dielectric stripline power divider whose outputs are connected by phase matched semi-rigid coaxial cable links to the inputs of eight identical output amplifier modules. The outputs of these modules are connected to the inputs of a stripline combiner by short phase-matched semi-rigid coaxial cable links. In order to minimize volume the combiner and divider were fabricated on the same piece of substrate.

Each of the output amplifier modules produces a minimum compressed power output of 35W over the 850MHz to 1400MHz frequency band and is capable of withstanding a short or open circuit on the output without failure, degradation or instability. The module has two stages of amplification. The input stage consists of a pair of nominally 5W GaAs FETs in a balanced amplifier configuration between dual conductor coaxial line 3dB couplers. The output of this unit is split by a broad band compensated Wilkinson power divider to drive two similar balanced pairs of nominally 10W transistors. A Wilkinson circuit similar to the divider combines the outputs of these two units. A design using carefully optimized transistor matching networks together with minimum combining losses provides a module capable of 35W minimum at 70°C case temperature. Each module contains its own thermal protection circuit and its own negative gate bias generator, and is thus protected against failure of the cooling system or power supply and associated cabling.

The amplifier operates at 100% duty cycle. Unlike class B amplifiers it will also operate with pulse input signals that have rise-times less than 50ns. Any non-class A amplifier is limited in pulse response because collector/drain bias current takes a finite time to rise through it’s bias circuit and transistor inductance's, from the quiescent current to the working current.

Cooling

Maintaining as low a junction temperature as possible in the transistors, is key to achieving maximum output power and device reliability. There is an 8°C temperature rise between flange and mounting base of the power GaAs FETs. This could be improved by soldering the transistor to the mounting base but this practice stresses the transistor thermally and makes manufacture and maintenance more difficult. The transistors are bolted directly to the module heatsink, with no barrier metals. It is essential that as high a polished finish as is possible is made under the devices for intimate metal to metal contact. The power modules are housed in aluminium enclosures with integral cooling fins running across the width of the module. The entire finned module is machined from the solid to ensure optimum heat transfer from the GaAs FETs, which are mounted directly to the inside surface of the enclosure. A similar type of construction is used for the driver amplifier, except that reduced cooling fins are required because of the lower power dissipation.

The amplifier modules were arranged as the 'bread' of a sandwich, with the combiner/divider as the 'filling', see figure 2. This produced two channels, top and bottom, through which air could be forced, by two ducted 400Hz axial fans at one end. Part of the power supply that aligns with the power amplifier module fins is itself finned. The cooling air mass flow provided by the two blowers, assuming no ram air assistance, gives a temperature rise of 11°C. This is small enough not to give rise to any differential phase or gain problems between the modules and to ensure that the 140°C maximum channel operating temperature is not exceeded.

Reliability

Thermal management was critical to achieving the required reliability figures. In order to achieve the heat removal required, high pressure fans were used. These have a quoted MTBF of 5000 hours. The required MTBF was 200 hours, the amplifier itself has a MTBF in excess of 2000 hours. The unit design is such that in the event of a single fan failure the unit will continue to operate within specification at all but the extremes of the operating envelope, (maximum temperature and altitude). Additionally no improvement as a result of the RAM air from the pod was included, which would obviously improve the situation. The use of multiple output modules also enhances availability, in that failure of a single module will only cause a 1.2dB reduction in output power. Failure of the driver module would cause total loss of output, but as this is a lower power (8W) module MTBF is enhanced by its operation at lower temperatures. The driver module is deliberately de-rated to further enhance its MTBF.

VSWR

Using class A GaAs FET transistors in a balanced configuration. This provides unconditional stability. Milmega amplifiers have been systematically tested into a short circuit over 0 - 180° phase variation and no damage or instability has been observed to date over several hundred measurements. The balanced class A stage is also stable with respect to out of band poles from circulators etc. At low frequencies each transistor of a balanced amplifier is terminated with 50 ohms resistive load, either on the input or on the output. No additional output isolation (with its inherent loss, n.b. 0.5 dB at 250W = 26W) is required.

Power Consumption

The solid state solution runs at an efficiency of ~17% when running at full RF output power. A typical TWTA would run at between 10 and 12.5%. Further power saving could be achieved by muting the amplifier supplier when not operating. A SSPA would be fully operation within milliseconds, whilst a TWTA requires a warm up period in the order of minutes.

Maintainability

The unit was designed such that the amplifier modules, the driver amplifier module, the switching power supply and the interface/BITE module, are all independently replaceable. The power divider/combiner can also be replaced but is entirely passive with no power components and therefore very unlikely to require removal. Amplifier module BITE indicates bias circuit faults. Disabling a module via a test point and observing the decrease in total output power allows individual sub specification modules to be identified. No tuning or adjustment is necessary when modules are replaced. As large quantities of the individual modules are manufactured it has been possible to refine the design to a high level giving performance repeatability.

Spectral Purity

For a SSPA of a balanced construction such, as that used, the 2nd and 3rd harmonics are typically better than -25dBc. This is substantially better than a TWTA whose structure produces 2nd harmonics of the order of –5 dBc. In this case, with the design frequency band reduced to less than an octave, the level achieved is greater than –30 dBc. Spurious levels in a SSPA, which generally are as a result of switching in the power supply, can easily be designed to –60 dBc. With care in the design and layout –80 dBc is achieved in production at Milmega where necessary.

Other advantages of SSPAs over TWTAs include a gain flatness of 1 dB max, (whereas the TWTA is typically 4 dB), and a noise figure of 10 dB max (compared with 30 dB typically for a TWTA).

Performance

Besides meeting all of the electrical design requirements the amplifier had to undergo extensive environmental qualification. This encompassed the following:

- Vibration
- Acceleration
- High temperature
- Low temperature
- Altitude
- Humidity
- Waterproof
- Fungus Resistance
- Shock
- Audio Noise

Additionally the amplifier had to meet EMI/EMC criteria based on MIL-STD 461 D and 462D for Class A1b equipment.

Three High Power Solid State Amplifiers P/N 603600-01 of the same configuration and issue status were used as samples in First Article Testing. The First Article Tests were split into three categories, Environmental Qualification Testing, Reliability Growth Testing and Electromagnetic Compatibility testing. One sample was tested for compliance with each category.

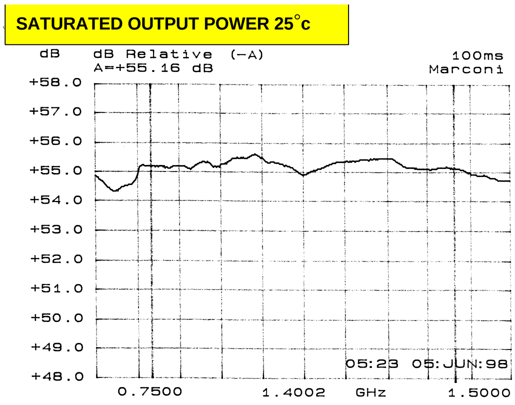


Figure 3 Output power performance across frequency band.

Refinement of the design during design assurance testing produced an environmentally and electrically compliant design.

Conclusion

Milmega delivered 6 pod mounted 250 W amplifiers to the customer, the last unit being delivered in the summer of 1998. The feedback from the customer is limited to generalizations for security reasons, however their comments are that they are very pleased with the amplifier, specifically in relation to the vast improvement in unit reliability.

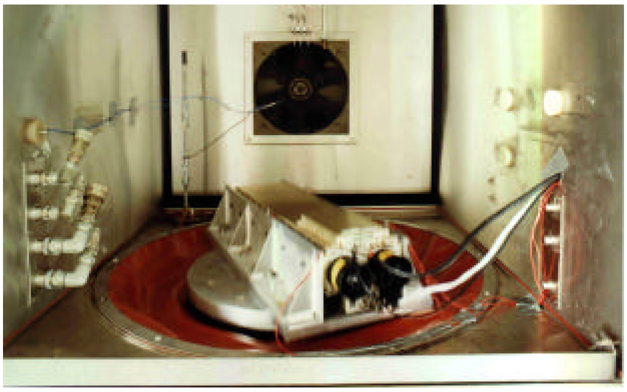


Figure 4 Pod mounted airborne 250W amplifier undergoing vibration testing