A 1.2 KW L-BAND SOLID STATE POWER AMPLIFIER FOR SPACE-BORNE SYNTHETIC APERTURE RADARS

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Abstract

The design results of a 500 watt amplifier which is used in a 1.2 KW solid-state, L-Band space qualified transmitter are described. A discussion of key design techniques which ensure the high reliability of this amplifier is presented along with test data. The power combining and special techniques for utilization of three of these amplifiers in a 1.2 KW synthetic aperture space-borne radar are also described.

Introduction

High power microwave solid state amplifiers have come of age for use in field environments. With the introduction and continuing improvement of high power, ruggedized power transistors the designer is now in a position to build amplifiers which essentially replace medium power TWT's and klystrons at frequencies up to 3.0 GHz. At L-Band radar frequencies transistors are now capable of 100-150 watts peak output. With these devices amplifiers with output powers of ten kilowatts are easily realizable. The solid state modular approach can result in these amplifiers having half the weight and volume and a conservative order of magnitude increase in field reliability when compared to their non-solid-state counterparts.

In addition, the decreasing dollars per watt (typically $0.75 - $1.00 per watt at L-band) and the maturing of vendor supplied transistors make both the design and purchase price of solid state amplifiers cost effective. In most designs the added feature of higher efficiency is also attained.

To achieve these high power levels advances in total amplifier design itself have kept pace with increasing transistor potential. Concentrated efforts in computer aided microwave design, high power packaging, and hybrid circuit fabrication have yielded reliable and affordable modules as building blocks toward multi-kilowatt powers. In addition, low loss, combining efficiency and redundancy have been incorporated into many high power splitter and combiner designs to maximize the versatility and performance of individual modules.

The remainder of this paper concentrates on the design and use of a high power solid state L-band module, a photograph of which is shown in Figure 1. By combining various numbers of these modules a 1.2 KW space-borne transmitter and a 6.0 KW TWT replacement amplifier have been built. Three of these modules and an output combiner package form the high power section of a synthetic aperture mapping radar which was built for the Jet Propulsion Laboratory. By repackaging the module for forced air cooling twelve of these modules are used to generate 6.0 KW for a 1250-1350 MHz tactical radar. This unit is shown in Figure 2. It has 73 dB of gain and contains its own integrated power supplies and cooling.

500 W Module Design

The heart of the power module design is a 110 watt bipolar microwave transistor. It is rated for 35 volts collector operation with a 6.4 dB minimum gain in the 1250 MHz to 1350 MHz frequency range. Over this range it produces 110-watts minimum output at a collector efficiency of 42 percent. These ratings are under pulse conditions of 50 μseconds and a duty factor of 0.05. As seen in the block diagram in Figure 3, eight are operated at derated collector voltages: the output six at 30 volts and the drivers at 28 volts. This is to ensure the low junction temperatures and thus high reliability which are required for space deployment. The same module when run at 35 volts input is capable of over 650 watts of output at 70^{o}C ambients.

Under derated conditions the module delivers 500 watts nominal output power with each output device delivering approximately 95-watts. The drivers deliver approximately 80 watts each. This power is split three ways in an in-phase 3:1 Wilkinson divider. This splitting technique was used for three reasons: (1) the input match of the final six devices is easily maintained over the required 20 MHz bandwidth and thus little driver-to-output isolation is necessary, (2) the driver device is significantly derated and will operate quite reliably into an output mismatch, (3) in-phase splitting usually implies in-phase output combining, and thus, lower output loss in general.

A circulator follows each output transistor to maintain both high reliability and intramodule combining efficiency. By using a circulator at some location after the transistors, complete module output SWR protection is provided. Further, by placing one after each transistor a lower loss transistor combiner can be designed. Since transistor-to-transistor isolation is provided by the terminated circulators, a non-isolating 6:1 impedance transformation network was developed and used as a combiner. It has 0.1 dB loss from 1250-1350 MHz and its amplitude and phase imbalance are 0.05 dB and 1.0^{o} respectively.

While in operation the 500 watt module supplies complete information concerning its operational status. This includes power output from each transistor, module output power, and chassis temperature. The individual transistor power monitoring is accomplished by microwave diodes which are built into the output circuitry of each transistor. All of these signals are conditioned within the module and sent to the telemetry down link for transmittal.

All of the RF amplification circuitry within the module is fabricated using thick films on 0.025-inch alumina substrates. These substrates are soldered to 0.040-inch moylbdenum carriers which are in turn attached to the aluminum chassis. The transistors and circulators are also mounted directly to the chassis for best heat transfer characteristics. The transistor leads, chip capacitors and detector diodes are soldered to the thick film circuitry.

The transistor output combiner is fabricated on 0.062-inch teflon fiberglass board. This material was chosen for its high power handling capability and its low loss per unit length.

As shown in Figure 4 the three production modules each exceed 500 watts in output power with total DC to RF efficiencies of 30% to 31% across the needed 1265 MHz to 1285 MHz frequency range. In addition, their amplitude flatness within this band is $\pm$0.1 dB. The modules have less than 1° phase deviation from a linear characteristic across this same band. Two-pulse cancellation residues are less than -65 dB-signal. Figure 5 shows the modules' output power and efficiency performance as a function of ambient temperature. Both decrease slightly with rising ambient and, therefore, transistor junction temperature. The peak junction temperature experienced at maximum ambients and at the end of the RF pulse is 155°C.

High Power Vacuum Problems

Throughout the design, high reliability and efficiency were emphasized. Special module and combiner design techniques were used to prevent the vacuum phenomena of corona and multipacting while maintaining good RF performance. Corona is the discharge of ionized gas molecules around an electrode which violently destroy the conductor and surrounding materials. Typically this happens in soft vacuum (10^{1}-10^{-3} TORR). Multipacting is usually a dual electrode oscillation (in the presence of an AC field) which manifests itself as a high VSWR and attenuation to the line signal. Typically this phenomenon occurs in a hard vacuum (10^{-2}-10^{-12} TORR) such as that in space. The RF voltages present in the modules and combiner are well above the minimum limits needed to sustain these conditions and proper design precautions where therefore taken.

Since the corona threshold voltage is sensitive to the produce of pressure and voltage gradient, it can best be suppressed by controlling pressure. This is especially true in most microwave transmission media, since lower voltage gradient techniques (i.e., smooth rounded surfaces of large radii) are not practical. As is shown by Hurley and Kuzakoff(2) the corona threshold voltage for a given geometry and power increases greatly at high and very low pressures. Therefore, the amplifiers and combiner suppress corona by venting all non-solid spaces to the outside vacuum. This design approach is made possible by the fact that operation of these units is not required until after orbit has been attained. The one exception to this venting design philosophy was the coaxial switches used in the combiner design. Here the approach taken was to maintain high pressure by hermetically sealing the switch. This was dictated by the need to maintain good RF performance while not incurring a multipacting problem due to too close spacings.

The multipacting problem as described by WOU (2) is an oscillation of free electrons in a resonant geometry. Although many conditions alter the exact threshold voltages required for this, the best suppressors of it are increased spacings between conductors and/or potting techniques. Both were used in the amplifiers and combiner. Line spacings were kept greater than 0.25-inches. Where high potential RF lines were required to come close to grounds, such as at connector launches onto microstrip or at circulator leads, an RTV was used to pot these potential problem areas. All high power connections in this system use TNC type connectors to ensure a solid dielectric around the high potential center conductor. In addition, solid dielectric cables were used exclusively. This same philosophy was followed in using the solid dielectric stripline medium for the combiner output package. Throughout the design and fabrication, care was exercised to ensure that both the materials and processes used to suppress multipacting did not introduce a potential corona problem. This was especially true in the choice of low outgasing materials, clean processing and careful placement of venting holes such that partial pressures would not built up in the units.

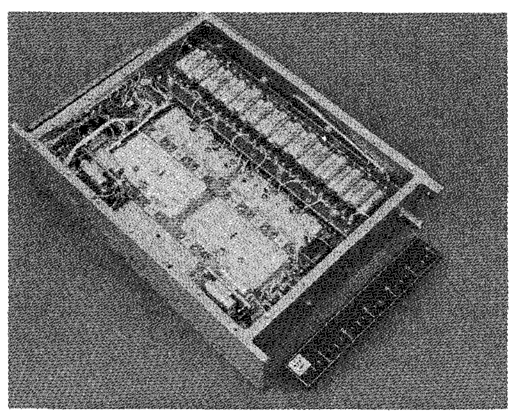

Figure 1. 500 Watt L-Band Module

Transmitter Combiner

The transmitter output combiner package is an integrated unit which was designed to provide the following:

- o Efficient combining of the 500 watt amplifiers.
- o A switchable redundant power chain capability.
- o Filtering of transmitter harmonics signals.
- o A circulator for steering transmitter and receiver signals.
- o A receiver calibration signal injection coupler.
- o Monitoring of both transmitter output and antenna reflected powers.

As mentioned above, there are three 500 watt modules per system. A switchable 3:1 combiner provides redundancy for the normal operational 2 module output power of 800 watts and permits operation at lower and higher power levels using one or three modules respectively. This combiner presents almost no additional loss to the system regardless of the number of inputs (up to three in this case).

As shown in the combiner block diagram, Figure 6, the combiner connects a common point summing junction either directly to a 500 watt module or to a short circuit. This connection is made by commanding a latching single pole-double throw coaxial switch. The short circuit is placed $3/4\lambda$ away from the summing junction such that when a power chain is off it does not load down the summing junction. The summing junction is followed by a one step impedance transformer which matches 25Ω to 50Ω . Only minimal mismatch power is lost from the "ON" chains through proper selection of certain combinations of switch positions and enabled power amplifiers as shown in Figure 7.

The summing junction and transformer are followed by a harmonic filter, T/R circulator and a second filter. These units provide 60 dB of harmonic rejection up to 8 GHz. Output forward and reverse power couplers and integrated telemetry signal conditioning are also provided in the unit.

The total output package has a transmitter to antenna loss of 0.9 dB and an antenna to receiver loss of 0.5 dB. The combiner amplitude and phase imbalance are 0.1 dB and 5° respectively.

As mentioned above, an integrated stripline medium was used. The unit is fabricated on teflon fiberglass board using a 0.25-inch ground plane spacing. Components such as the circulator, RF attenuators and detector diodes are soldered directly to one board before clamping the two boards together. Potting is applied later to areas of possible multipacting. The combiner is shown in Figure 8.

Conclusion

High power solid state amplifiers and medium power transmitters are attainable at microwave frequencies. At L-band multi-kilowatt units are now available for field usage at a lower cost of ownership than their tube counterparts. With the proper design techniques, such amplifiers can outperform TWT's and klystrons while attaining substantial increases in reliability. By merging this capability with good vacuum orientated practices space qualified solid state amplifiers have been built.

References

(1) H.S. Hurley and R.J. Koyakoff "RF Multicoupler Design techniques to Minimize Problems of Corona, Multipuction and Stability" NASA Report CR-61387, December 31, 1971.

(2) Woo, R. "Final Report on RF Voltage Breakdown in Coaxial Transmission Lines" FPL Tech Rep 32-1500 (NASA) Oct. 1970.

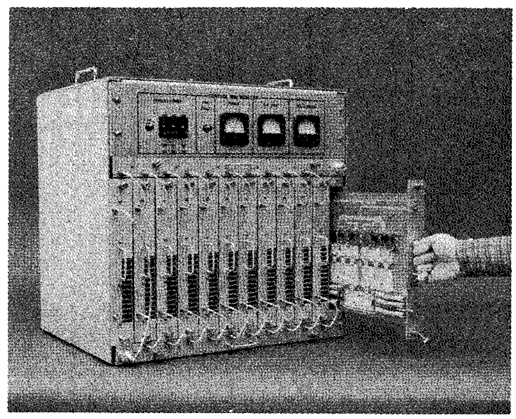

Figure 2. 6.0KW Solid State Amplifier

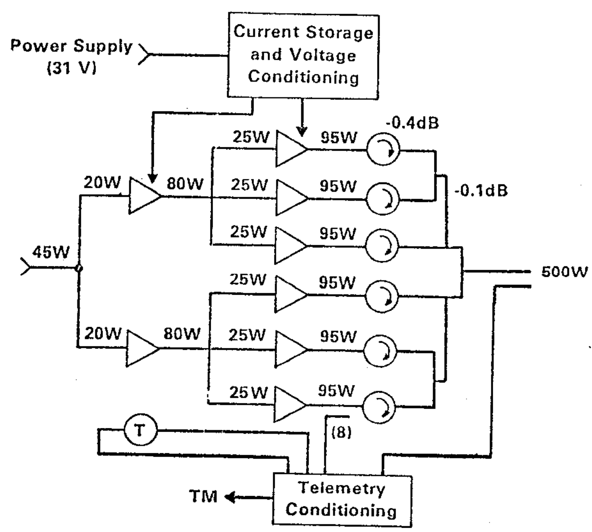

Figure 3. 500W Amplifier Block Diagram

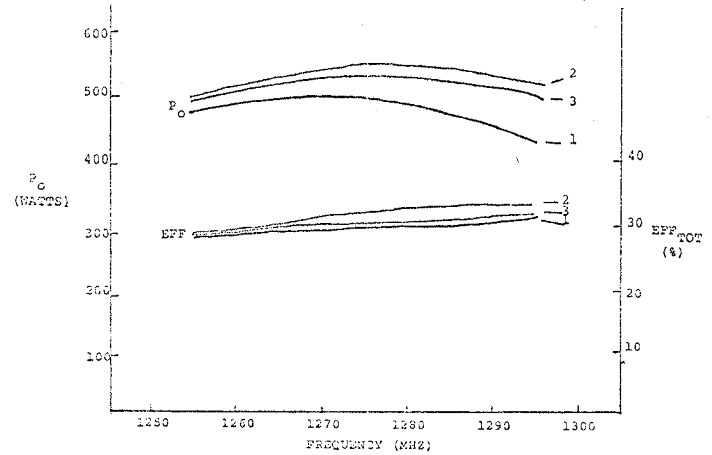

Figure 4. 500-Watt Modules' Frequency Response

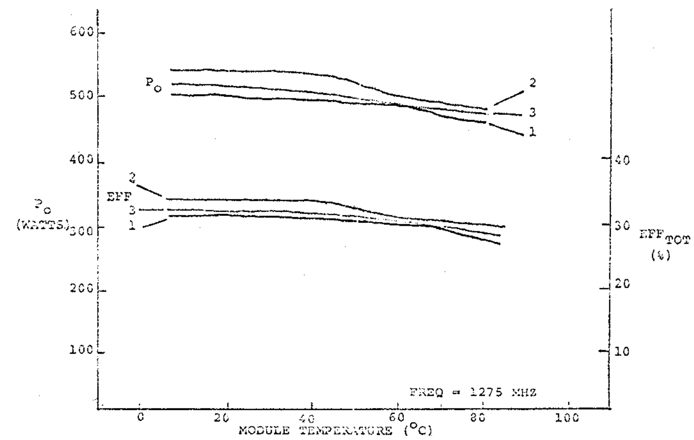

Figure 5. 500 Watt Modules Temperature Response

COMBINER OPERATION

# of Power Chains	# of Switches Shorted	RF Generated Power	Combiner VSWR	Mismatch Loss
1	2	500 W	2:1	55 W
2	1	1000 W	1:1	0 W
3	0	1500 W	1.5:1	60 W

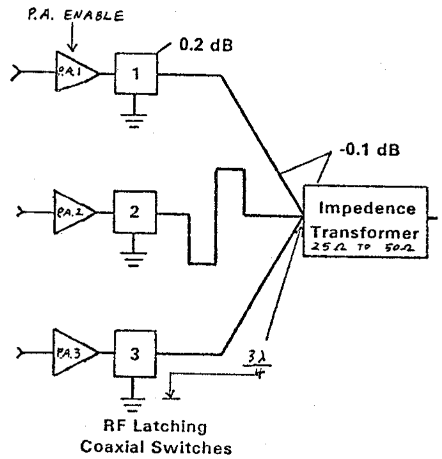

Figure 7. Combiner Operation

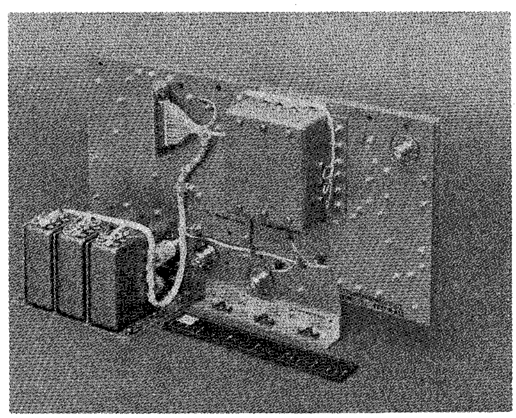

Figure 8. Transmitter Combiner Package

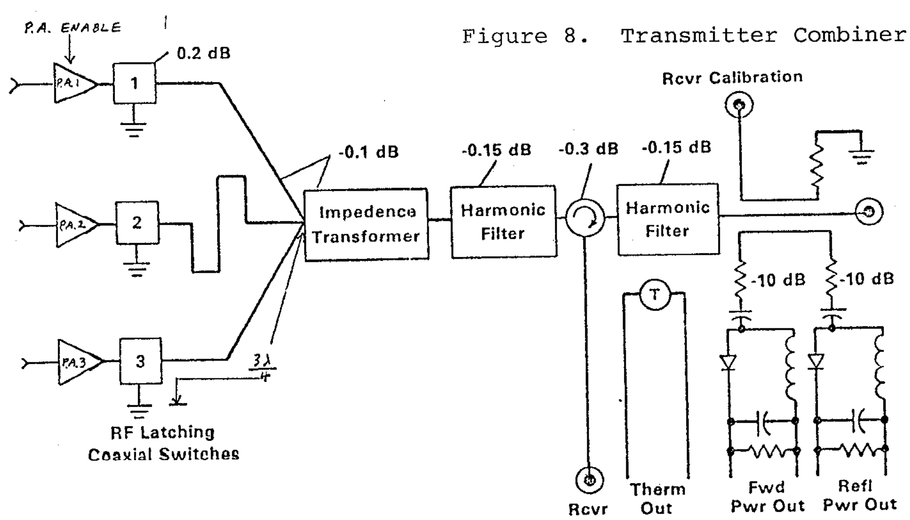

Figure 6. Combiner Package Block Diagram