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SOLID-STATE POWER AMPLIFIERS FOR SATELLITE RADAR ALTIMETERS

This article describes the development of two solid-state power amplifiers, operating at C and Ku band, for the TOPEX and Spinsat satellite radar altimeters, respectively. To reduce the power requirement, gated solid-state amplifiers were chosen for these applications instead of the traveling wave tube amplifiers used in previous altimeters. The solid-state amplifiers provide a minimum of 20 W RF output power at C band and 6 W at Ku band.

INTRODUCTION

High-resolution pulsed radars have been used since the early 1970s to remotely sense the oceans and measure the shape of the ocean surface along the subsatellite track. Features such as currents, tides, and wave heights have been measured with ever-increasing accuracy as the technology has advanced. Data from such satellite radar altimeters have been used to support research in geodesy, bathymetry, mesoscale oceanography, tides, ice topography, winds, and waves. For well over ten years, APL has participated in the development of altimeters, beginning with Geos-C, through Seasat-A, Geosat-A, and now TOPEX and Spinsat. Development of the latter two altimeters is in progress. Table 1 gives the characteristics of the transmitted waveform for some of the altimeters.

Earlier altimeters used gridded traveling wave tube amplifiers (TWTA) that were modulated to conserve DC power. Short pulse widths ($\leq 3.2 \ \mu s$) and high peak RF output power were used. The Hughes model 852H 2-kW TWTA provided the required signal amplification. For the Geosat-A altimeter, a change in the TWTA was made to achieve longer operating life. The pulse length was increased and the peak power decreased. The Watkins–Johnson model WJ-1226-10 continuous-wave (CW) TWTA amplified the signal. An RF switch near the input of the TWTA provided the final pulse shaping. For the TOPEX (Ku- and C-band) and the Spinsat (Ku-band) altimeters, both Watkins–Johnson TWTA's and Electromagnetic Sciences, Inc., solid-state amplifiers will be used. We will first give a short, simplified description of a TWTA and follow with a discussion of the solid-state amplifiers.

TWTA

A TWTA comprises a TWT and a power supply that produces the required voltages for the beam, the helix, and other circuitry. There are also control and telemetry circuits, as required by the application. The TWT is composed of an electron gun that can produce an electron beam and a structure that supports a slow electromagnetic wave and also keeps the beam focused. A helix is commonly used for the structure because it can produce a wave that has a propagation velocity less than the speed of light, so that the electron beam and the wave can travel with approximately equal velocity. The veloc-

Table 1. Characteristics of the transmitted altimeter waveforms.

	Geosat-A[a]	TOPEX[b]		Spinsat[c]
Frequency (GHz)	13.5	13.6	5.3	13.6
Bandwidth (MHz)	320	320	320/100	320
Peak RF power (W/min)	22	22	20	6
Average RF power (W)	2.3	9.6	2.1	0.6
Pulsewidth (μs)	102.4	102.4	102.2	102.4
PRF (Hz)	1020	4272	1012	1020
Output amplifier	TWTA[d]	TWTA[d]	SSA[e]	SSA[e]
Amplifier DC power (W)	62	70	24	11

[a]Geosat—Navy geophysical/geodetic satellite
[b]TOPEX—NASA Ocean Topography Experiment
[c]Spinsat—Navy special purpose inexpensive satellite
[d]Traveling wave tube amplifier
[e]Gated solid-state amplifier

ity is related to the obtainable output power, high-power tubes having a higher velocity than the low-power tubes. The electron beam therefore continuously interacts in approximate synchronism with the field of the wave traveling along the structure. Figure 1 shows a very simplified TWT. An electron stream, produced by the electron gun, travels along the axis of the tube and impinges on the collector. The beam is kept focused with a longitudinal static magnetic field applied along the beam axis. The RF energy is coupled to the helix at the input and output ports. The longitudinal component of the field interacts with the electron beam and modulates the beam, which, in turn, interacts with the waves on the helix. This continuous mutual interaction appears along the length of the tube. Direct current energy is given up by the electron beam to the wave, producing an amplified wave. A separate grid can be used to achieve pulse modulation and reduce DC power consumption if the full saturated output capability of the amplifier is not required.

FROM TWTA'S TO SOLID-STATE AMPLIFIERS

The first altimeter use of a solid-state power amplifier, gated to preserve power, was for the TOPEX Advanced Technology Model (ATM) altimeter, a brassboard predecessor of the TOPEX flight altimeter. The ATM was to prove the design concept for a high-precision, dual-frequency altimeter, using a primary channel at Ku band and a secondary channel at C band. The redundant, dual-frequency TOPEX flight altimeter requires four final amplifiers: two for Ku band and two for C band. For the primary Ku-band channel, TWTA's, similar to the successful and proven Geosat-A Ku-band TWTA, will be used. For the secondary C-band channel, possible alternatives to TWTA's (which require large DC power; see Table 1) were considered.

When the ATM began in 1983, there were no space-qualified C-band TWTA's available that would meet the TOPEX performance requirements and that could be controlled to minimize the power consumption. Solid-state devices offered an attractive alternative. The 6-W gallium arsenide (GaAs) field effect transistor (FET) devices were becoming available that could be combined to give
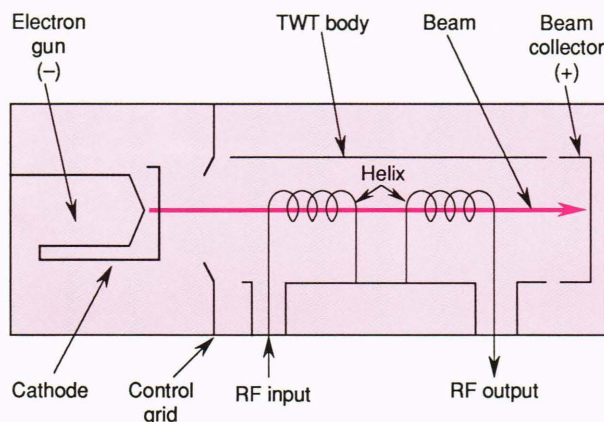
the required 20-W output power. The 20-W solid-state amplifier, built for the brassboard TOPEX ATM altimeter and now being fabricated for the flight altimeter, is described in this article. Electromagnetic Sciences, Inc., of Norcross, Ga., was competitively selected to design, fabricate, and test, under contract to APL, the solid-state amplifiers discussed in this article. After the ATM C-band amplifier was developed, a similar amplifier at Ku band was produced that will be used for the Spinsat altimeter.

The Spinsat altimeter is required by the Navy to have Geosat system performance, with reduced weight, size, and DC power consumption. Since system requirements can be met with lower RF output power, a 6-W Ku-band solid-state amplifier will be used. Work on the amplifier began shortly after the development of the C-band ATM amplifier for an altimeter that preceded Spinsat. The performances of the then-available Ku-band GaAs FET's, including those from Fujitsu and NEC, were compared, and the optimum devices for the amplifier were chosen. An engineering model amplifier, described in this article, was built by Electromagnetic Sciences, Inc. It will be refurbished for the Spinsat altimeter with rebuilt electronics boards, using upgraded parts.
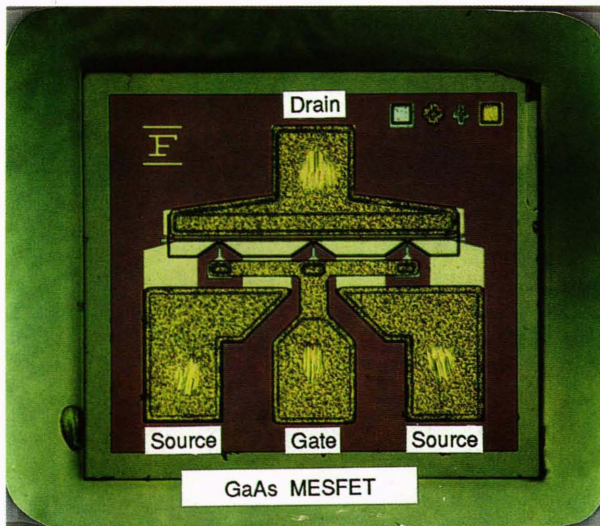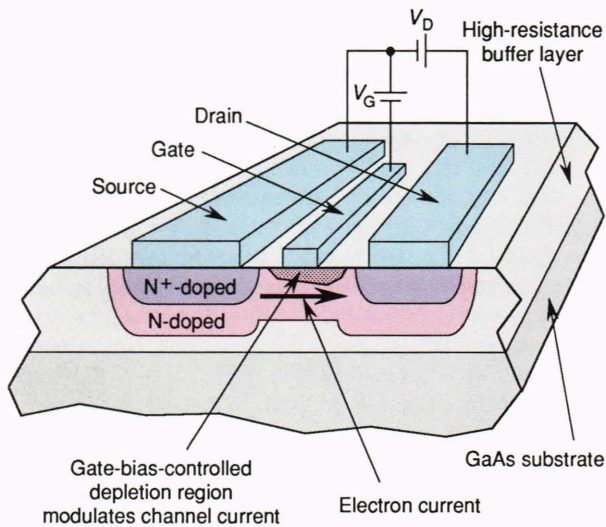
The following sections discuss the C-band 20-W amplifier for TOPEX and the Ku-band 6-W amplifier for Spinsat. The last section describes the performance of the TOPEX and Spinsat engineering model amplifiers and, for illustrative purposes, also gives some of the performance parameters of the Geosat-A TWTA. Before describing the two amplifiers, we will discuss the solid-state amplifier gating options.

PULSED OPERATION OF GaAs FET AMPLIFIERS

GaAs FET's are semiconductor devices that are used for microwave applications spanning the frequency range from below 3 GHz to above 200 GHz. They have been extensively described in the open literature, and the intent here is to make the reader familiar with the terminology used in this section.

Figure 2 illustrates a type of FET (a metal gate Schottky FET), showing the source, gate, and drain electrodes. Figure 3 shows the GaAs FET packaged as a miniature hybrid, typical of a power amplifier. The gate length and width, as well as the source-gate and drain-gate separations, are critical; they determine the frequency of operation and application (e.g., low noise, high power, or high efficiency). The optimum DC operating point (bias point) for an application is selected on the basis of functional requirements. The bias circuits (internal or external) energize the gate, drain, and source; the electrode bias must be chosen carefully, so as to prevent undesired conditions that could harm the devices. The gate and drain can be controlled or pulsed to conserve power.
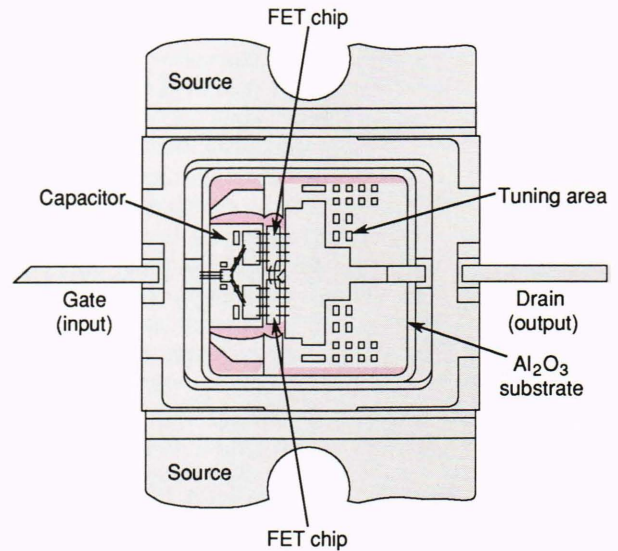
Many articles have discussed pulsed operation of GaAs FET amplifiers; the bibliography lists a few. Pulsed operation has several advantages over CW, such as lower power dissipation and lower operating temperatures, which result in higher efficiency and reliability. The tem-

Figure 1. A simplified helix TWT.

Labels: Electron gun (−), TWT body, Beam, Beam collector (+), Helix, Cathode, Control grid, RF input, RF output

Figure 2. Top panel is a cross section of the metal gate Schottky field effect transistor (MESFET), shown in the bottom panel, illustrating the principle of operation. V_G is the gate supply voltage, and V_D is the drain supply voltage.

Figure 3. Diagram of a typical GaAs FET package.

perature of the channel (the area in the active layer under the gate) is usually kept as low as possible, to extend the reliability and life of the FET. Many articles listed in the bibliography discuss the use of pulsed operation to obtain higher output power than would be obtainable with CW and describe operation with short pulse widths and short duty cycles. For the altimeter power amplifiers discussed here, pulsed operation is used primarily to conserve power, rather than to obtain higher output power. To obtain pulsed operation, the gate is switched off between pulses or the drain is switched.

Pulsed operation of a GaAs FET can be most easily obtained with gate switching, where the gate voltage is switched between the normal operating bias and pinch-off (where the drain current is stopped). The device is effectively cut off by applying a voltage to the gate that is larger than the pinch-off voltage of the GaAs FET. The device is then turned back on with a positive-going pulse (decreasing the effective negative gate-to-source voltage), which allows the GaAs FET to draw its normal operating current. This operation does have some disadvantages. The power GaAs FET's do not completely pinch off, resulting in some leakage drain current, which limits the attenuation achievable in the off state and also causes some continuous heating of the FET's. For the altimeter amplifiers, such effects are very small. Also, the GaAs FET gate breakdown voltage, where the FET could potentially be damaged, limits the allowable amplitude of the gate-switching pulse and therefore the pinch-off current. A great advantage to the gate-switching method, in addition to its simplicity, however, is that gate pulsing can result in very fast switching speeds.

Pulsed drain operation is accomplished by switching the drain voltage from 0 V to the normal operating drain voltage and current. This eliminates the large gate voltages but is more complex in that it requires both a fast current driver and the ability to switch high drain currents. Significantly lower switching speeds are attainable, as compared to gate switching.

For the altimeter amplifiers, gate switching is used to permit the required fast switching. Also, the TOPEX amplifier has large drain currents (approximately 11 A) that would have to be switched for drain switching, thus placing heavy stress on the already complex amplifier power supply.

TOPEX C-BAND
20-W SOLID-STATE AMPLIFIER

Figure 4 is a block diagram of the C-band amplifier. The amplifier has three main sections:

1. A microwave section, composed of three subsections:

a. A low-power section that provides limiting, RF input power monitoring, level adjustment over temperature, and input-signal amplification.

b. A medium-power section that amplifies the drive signal for the high-power section and provides signal pulse shaping and amplifier isolation.
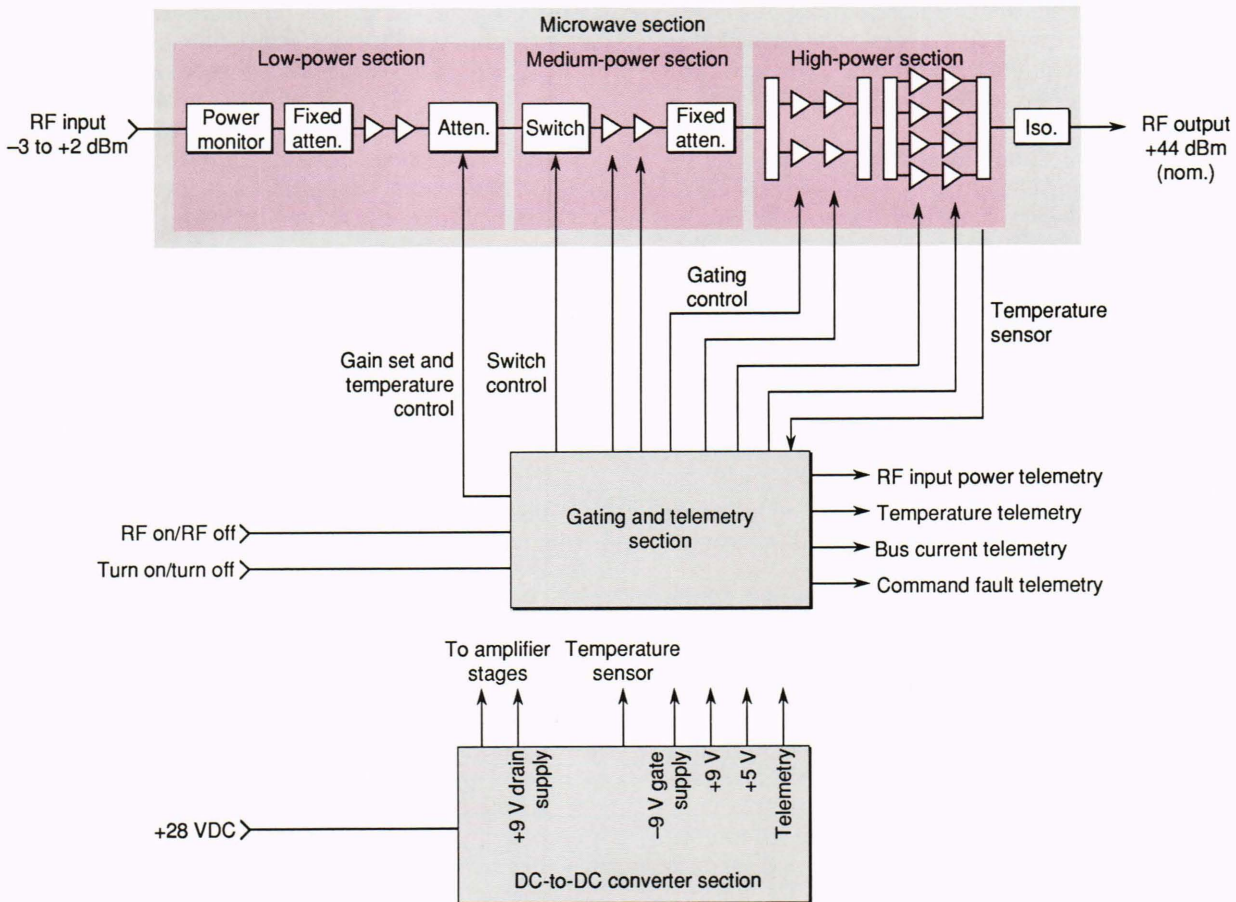
Figure 4. Block diagram of the C-band power amplifier.

c. A high-power section that amplifies the RF signal to the required output power level.

2. A gating and telemetry section that accepts the amplifier-power (turn-on/turn-off) and switch (RF-on/RF-off) commands to control the amplifier, biases the gates of the GaAs FET's to pinch-off between radar pulses to conserve DC power, and returns the required telemetry signals to the altimeter.

3. A power supply (DC-to-DC converter) section that converts the spacecraft bus voltage to the required amplifier secondary DC voltages, supplies GaAs FET energy storage during the pulse to minimize droop across the pulse, provides filtering to protect the spacecraft bus from turn-on and turn-off transients as well as drain-current load switching, and provides self-protection and current limiting.

The TOPEX C-band solid-state power amplifier contains high-reliability, space-qualified parts and is tested to ensure compliance with the spacecraft electromagnetic compatibility and environmental requirements.

Microwave Section

Figure 5 is a photograph of the microwave and the telemetry and gating sections of the TOPEX engineering model. The ATM amplifier, discussed earlier, is similar,
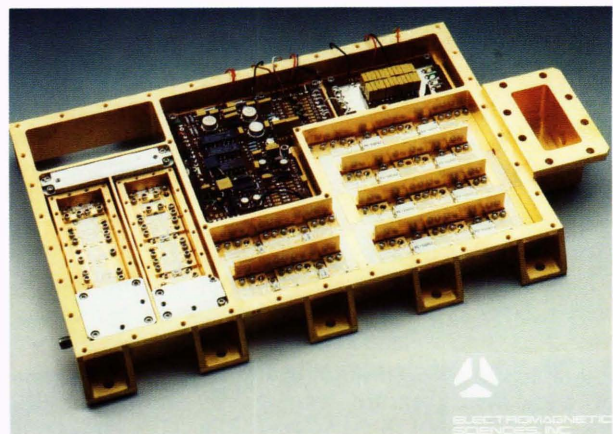

Figure 5. The C-band solid-state power amplifier microwave and telemetry and gating sections.

except that a single-section driver chain instead of the two-section chain shown in Figure 5 was used to drive the final output stages. The ATM amplifier performed satisfactorily but had some specification deviation, notably phase linearity, caused by the difficulty of impedance-matching the high-power GaAs FET's to 50 Ω, ex-

ternal to the FET, over the 320-MHz bandwidth at 5.3 GHz. The flight amplifier engineering model uses internally tuned GaAs FET's (i.e., there is an impedance-matching network internal to the GaAs FET package) and has met or exceeded phase performance requirements.

The low- and medium-power amplifier sections provide gain to amplify the input RF signal to the level required by the high-power amplifier section. Both sections also perform other functions. The low-power section limits the input RF signal and provides temperature compensation so that a controlled drive level is presented to the high-power section. The medium-power section switches the RF signal to perform the final pulse shaping and provides additional isolation between pulses (the GaAs FET's are pinched off). The high-power section provides the final RF signal amplification to the required output power level and contains the temperature sensors used for temperature compensation. The following sections lead the reader through a detailed description of the microwave section shown in Figure 4.

Low-Power Section. An RF signal of -3 to $+2$ dBm is applied to the low-power section input power monitor, where it is sampled and where a telemetry voltage proportional to the input power is supplied to the spacecraft. The input power monitor aids in fault isolation if there is a failure in the transmit chain. From the power monitor, the input signal is applied through an attenuator to the NE67383 GaAs FET, which is biased to minimize the noise figure. The latter is related to the RF noise produced by the amplifier (particularly important between pulses when the altimeter is receiving the low-level return from the ocean surface that must not be degraded by the amplifier noise). The next NE67383 performs the limiting function and is biased to minimize the AM-to–PM conversion (where input amplitude variations translate to output phase variations). The output of the second GaAs FET, approximately $+12$ dBm, is applied to the variable attenuator. Its attenuation is changed to compensate for the gain variation over temperature of the amplifier so that the drive level to the output device is maintained at the proper level. Temperature sensors in the high-power section control the attenuator. The output of the variable attenuator is applied to an RF switch in the medium-power section.

Medium-Power Section. The switch, controlled by the altimeter, establishes the proper pulse shape and provides additional isolation between pulses. The output signal from the switch is amplified to $+20$ dBm (nominal at ambient temperature) with a variation of ± 0.2 dB, using two NE800196 GaAs FET's. The first NE800196 is biased at approximately $+5$ V to optimize DC power consumption; the second is biased at $+9$ V to obtain the required output drive for the high-power section. The gates of the NE800196 GaAs FET's, as well as those in the high-power section, are biased to pinch-off between the pulses under control of the gating and telemetry section. The gates are biased to the operate state 5 μs before the RF pulse, that is, 5 μs before the closure of the RF switch. The time required for the GaAs FET's to change from the pinch-off to the operate state, where

all performance parameters must be met, is less than 5 μs, but this time was chosen on the basis of timing signals set within the altimeter. An optional fixed attenuator may be used to set the drive level to the high-power section. Its value depends on the actual gains of the GaAs FET's in the medium- and high-power sections.

High-Power Section. The output drive from the medium-power section is applied to the high-power section. A coupler divides the signal between the two drive chains. Each chain is composed of cascaded NE800196 and NE800495-5 GaAs FET's. The output from each chain is approximately $+26$ dBm. The chains are combined in a coupler identical to the input divider and then applied to two 2-way couplers that form the 4-way divider for the final amplification stages. Each stage is composed of cascaded NEZ 5055-3A and NEZ 5055-6A GaAs FET's. The latter provide about 6 W, with 7-dB gain and 35% power-added efficiency. They are internally matched to about 50 Ω and require limited external tuning compared to the devices used for the ATM. The outputs are combined in a coupler identical to that used on the input. A transition from microstrip to waveguide is made, and the signal is fed through an output waveguide isolator to the output. Because several performance tests require the microwave section to operate continuously, the output isolator can absorb the full 20 W average power. The use of four output stages with an isolated power combiner provides some degree of graceful degradation in the event of a failure of a GaAs FET module, without adding excessive complexity to the circuit. For example, the failure of a module in the 4-way chain would theoretically reduce the output power by 2.5 dB. The balanced input driver also provides for some graceful degradation. A failure of one arm would reduce the drive level by approximately 6 dB but would result in a lesser effect on the total output power because the final stages are in saturation.

Gating and Telemetry Section

The gating and telemetry section performs several control functions and provides four telemetry outputs to the altimeter.

Primary among the control functions is gating off the GaAs FET's between radar input pulses to conserve DC power. In response to the turn-off command (see Fig. 4), the gating circuit switches all of the power GaAs FET's in the medium- and high-power sections from the operate state to the pinch-off state. A significant amount of power savings results because the amplifier's duty cycle is typically 12.5%. Another control function of the gating and telemetry section is to switch the RF signal. It accepts the RF-on/RF-off command and provides the drive required to transition the RF switch between a high-isolation state (about 45 dB) and a low-insertion-loss state (about 1.4 dB), with transition times of less than 50 ns. The third main control function of the section is to provide temperature compensation for the GaAs FET's. Part of the control portion of the section consists of a combination resistor/thermistor network that temperature-compensates the gain of the driver amplifier by providing more attenuation in the variable attenuator as the

temperature is decreased. Two resistor adjustments control both the attenuation slope versus temperature and the offset level of attenuation at a fixed temperature.

The telemetry portion of this section provides four telemetry outputs to monitor the RF input power, the temperatures at two locations, and the bus current, and to determine an incorrect amplifier turn-on command. The RF input power level is detected by the power monitor and amplified. The bandwidth of the amplifier is wide enough that the pulse shape of the RF input is reproduced. Two indicators of amplifier temperature are provided to the altimeter via thermistors. One is located near the high-power GaAs FET's in the high-power section, and the other is near the power metal-oxide-silicon FET's (MOSFETs) on the power supply section. Bus current monitoring is achieved by sampling the current of the power supply section and amplifying the signal. In that case, the amplifier must filter out the 1.22-kHz pulse repetition frequency and the 160-kHz power supply frequency components, and provide an indication of the average bus current. The incorrect altimeter turn-on command telemetry is provided in conjunction with the control function of this section. If the turn-on command exceeds 120 μs pulse width or is shorter than 650 μs pulse repetition period, the gating control to the amplifiers is disabled (amplifiers are off) and a logic 1 is provided on a continuous basis on the command fault telemetry line (Fig. 4). Only after receiving at least two pulses of the correct pulse width and pulse repetition period is the gating control restored to normal. This is accomplished by the amplifier and does not require altimeter intervention. The command fault telemetry line is then restored to a continuous logic 0.

DC-to-DC Converter Section

The power supply section, also referred to as the DC-to-DC converter, converts the unregulated bus voltage to the various regulated voltages required by the component parts of the microwave amplifier. Specifically, the converter provides a temperature-compensated +9-V line that supplies power to the pulsed GaAs FET's and +5-V, −9-V, and +9-V lines for other circuitry. The converter also provides for bus current monitoring, current limiting, and an override of the current limiting. Finally, the converter provides substantial energy storage so that approximately 11 A (peak-to-peak) of current is delivered to the GaAs FET's with a 1.22-kHz pulse repetition rate and a 12.5% duty cycle, with only 80 mA peak-to-peak current ripple observed at the spacecraft bus.

The power converter is composed of a high-power and a low-power section. The principal function of the high-power section is to provide the 9-V output for the GaAs FET drains. The low-power section supplies the other voltages required by the amplifier. The low-power section also provides the overall control functions of the converter, including a start-up regulator, current-limit shutdown, current-limit override, and undervoltage shutdown.

Figure 6 shows a block diagram of the converter. Spacecraft power is fed to an electromagnetic-interference (EMI) inhibiting filter that, in turn, feeds the flyback converter and start-up circuit. A dual-phase, dual-loop
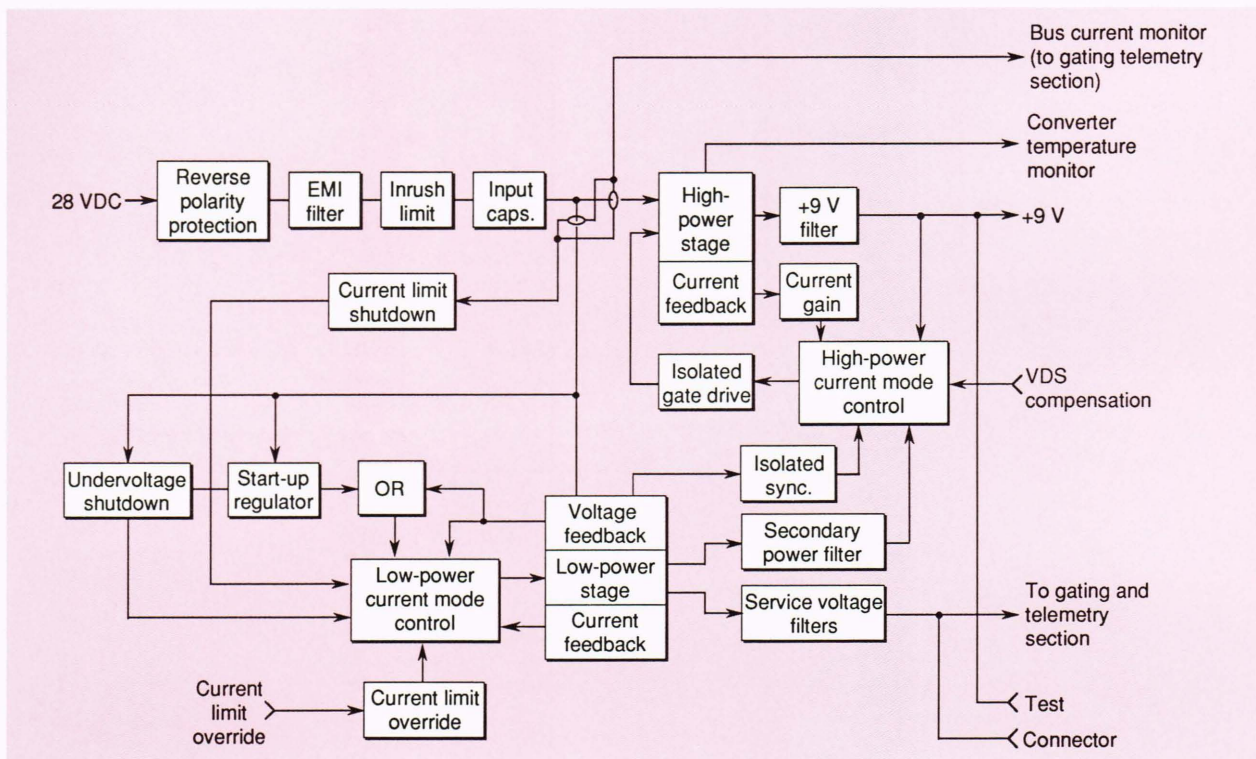

Figure 6. Block diagram of the DC-to-DC converter.

(inner current and outer voltage) flyback converter operating at 160 kHz is used. A control logic provides feedback action to regulate the output voltages. The desired voltages are fed via an output filter and distribution circuit to the amplifier sections requiring power.

The 160-kHz operating frequency was chosen to reduce the size of the magnetics without significantly reducing efficiency. An additional benefit of the selected operating frequency is that a wider control loop bandwidth is allowed, which improves recovery of the converter. When the microwave amplifier is commanded on for 102 μs, the converter voltage control loop responds to the difference between the 9-V line and the 9-V reference. The response of the control loop is to increase the duty cycle of the flyback converter to a maximum of 50%. The fast recovery of the converter to load changes provides excellent regulation and reduces the amount of energy storage capacity in the secondary circuit.

Approximately 400 μF of capacitance is distributed in the 9-V pulsed line wiring between the power converter output and the GaAs FET drains. At each power FET location, a 22-μF capacitor is used to reduce dI/dt current transients in the wiring. Without these capacitors, a large voltage transient is induced at the GaAs FET drain terminals. This voltage transient must be reduced because any voltage transient on the saturated output stages will distort the pulse rise time and amplitude linearity across the pulse.

SPINSAT Ku-BAND 6-W SOLID-STATE AMPLIFIER

The Spinsat Ku-band amplifier (Figs. 7 and 8) is similar conceptually to the TOPEX C-band amplifier. Before the development of the Ku-band unit, a study was undertaken to investigate the GaAs FET devices then available to determine which, on the basis of experience gained from the C-band ATM amplifier, would meet the Ku-band requirements. The NEC and Fujitsu GaAs FET's met those requirements most closely, and high-power output stages were fabricated using those devices. The stages were tested and their performances compared relative to the overall altimeter requirements. The NEC device offered better output power, whereas the Fujitsu device had better power-added efficiency but lower output power. The latter also did not appear to be as closely matched in phase performance from device to device as were the NEC devices. This is an important consideration because the input signals to the final power combiner must be matched in phase so that maximum output power can be obtained. After further evaluation of the test data and other altimeter requirements, the NEC devices, described in the next section, were selected.
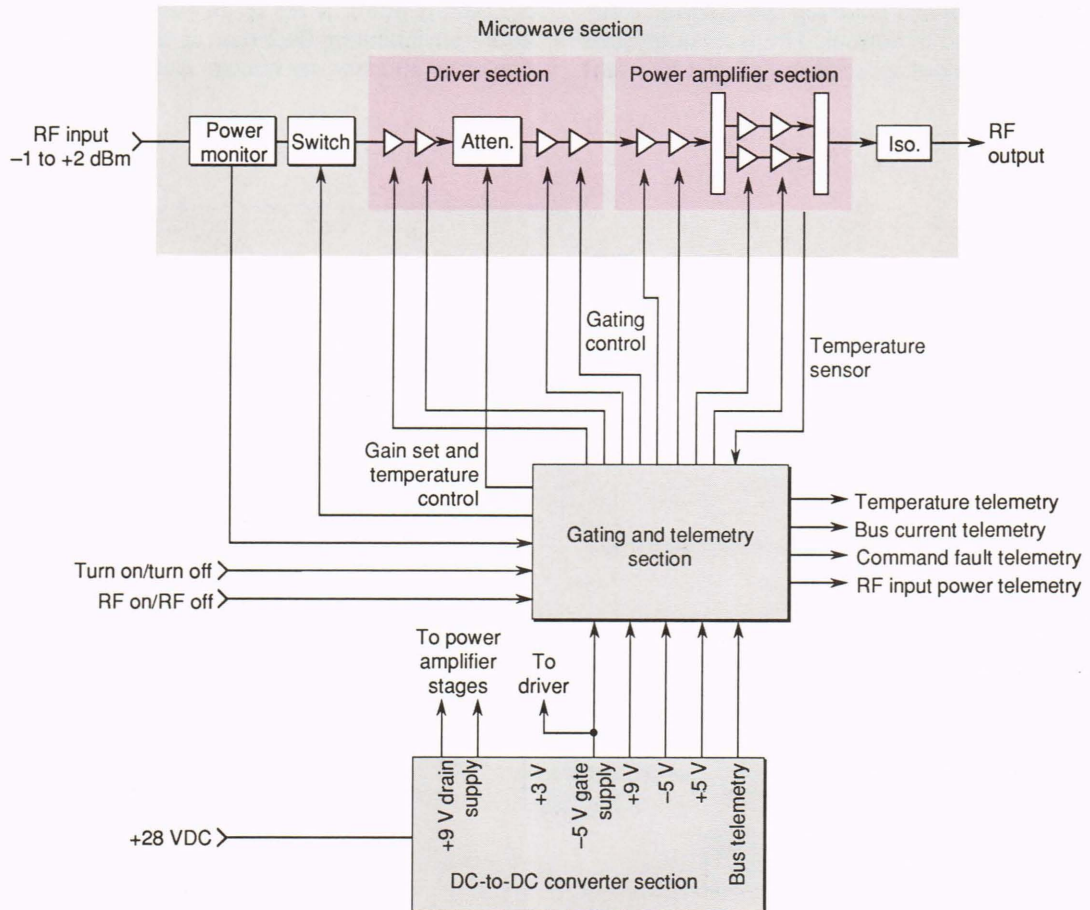

Figure 7. Block diagram of the Ku-band power amplifier.
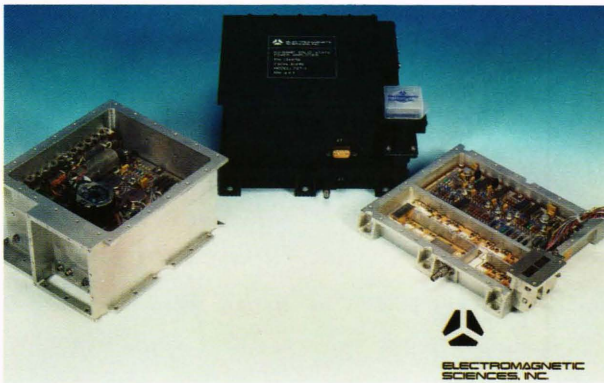
Figure 8. The Ku-band solid-state power amplifier.

The Ku-band amplifier and the C-band amplifier are composed of similar subsections, but the microwave section of the Ku-band amplifier has fewer GaAs FET's, because less gain is required to achieve the lower output power. The amplifier microwave section is composed of the input power monitor, RF switch, driver, and power amplifier sections.

Microwave Section

The input power monitor, switch, and attenuator in the driver section perform the same functions in the Ku-band amplifier as in the C-band amplifier. The driver section also contains two NE71083 GaAs FET's before the attenuator that amplify the input signal from between −1 and +2 dBm to about +12.5 dBm. Again, the driver section provides limiting and low AM-TO-PM conversion as discussed in the section on the C-band amplifier. The two NE900175 GaAs FET's after the attenuator provide further signal amplification.

The two driver stages in the power amplifier section, the NE900474 and NE1313-2, amplify the signal to about 32.4 dBm. The GaAs FET's before the NE1313-2 are not internally matched and require external tuning over the 320-MHz bandwidth. The higher power GaAs FET's have internal matching close to 50 Ω at about 13 GHz and require limited external tuning. The signal from the drive chain in the power amplifier section is divided by a microstrip divider and applied to the two final output devices, the NE1313-2 and NE1313-4 GaAs FET's. The former has a nominal 2-W output and the latter a nominal 4-W output. A transition is made from microstrip to waveguide at the output of the final amplification chains, and the signals are then combined to provide a minimum of 6 W of power at the output of the amplifier.

Gating and Telemetry Section

This section is functionally equivalent to the corresponding section of the C-band amplifier. The Ku-band amplifier control circuit is a modification of the control circuit used for the C-band ATM amplifier. In the latter, each GaAs FET gate bias was controlled by an individual bipolar transistor circuit; for the Ku-band circuit, each bipolar transistor circuit controls two GaAs FET gate bias points.

DC-to-DC Converter

The DC-to-DC converters for both the C-band and Ku-band amplifiers are functionally equivalent. Each operates from a chassis-isolated input power bus and provides the required regulated voltages for the components of the microwave amplifier. The pulsed load demand of the Ku-band amplifier, however, is smaller than its C-band equivalent. The C-band amplifier requires about 11 A, peak (1.4 A, average), whereas the Ku-band amplifier requires about 5.5 A, peak (0.6 A, average).

For the Ku-band converter, a 40-kHz operating frequency is chosen for high efficiency and reduced high-frequency EMI filtering requirements. The Ku-band converter uses the amplifier turn-on command signal to change the gain of the feedback loop during the current drain interval. The combination of the lower peak load and the use of the turn-on command to increase the converter duty cycle during peak loads allows the use of a narrower bandwidth control loop and lower converter operating frequency.

PERFORMANCE SUMMARY

The performance of the gated C-band and Ku-band solid-state amplifiers for the TOPEX and the Spinsat altimeters, respectively, is given in Table 2; the performance of the Geosat-A CW TWTA is also given for illustration. The performance of the TOPEX Ku-band CW TWTA is expected to be similar to that of the Geosat-A unit. Note that all amplifiers have been subjected to electromagnetic compatibility and environmental testing (thermal, thermal vacuum, random, and sinusoidal vibration). Specific requirements differ somewhat between the altimeters, and only the temperatures over which the amplifiers were tested are given in the table. The data show the minimum performance over all environmental conditions and bus voltages. The TOPEX and Spinsat data are based on tests performed on the engineering models, which are equivalent in form, fit, and function to the flight amplifiers.

CONCLUSION

This article has described the development and performance of two gated solid-state amplifiers at Ku band and C band that will be used for the Spinsat and TOPEX altimeters, respectively. It has been shown that gated solid-state power amplifiers are an attractive alternative to TWTA's for applications where power consumption (and perhaps weight and volume) is of prime importance.

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Table 2. Electrical performance of the Geosat-A TWTA, TOPEX C-band SSA, and Spinsat Ku-band SSA.

Test parameter	Geosat-A Ku-band TWTA	TOPEX C-band SSA	Spinsat Ku-band SSA
Frequency (GHz)	13.25 to 13.75	5.14 to 5.46	13.44 to 13.76
Temperature (°C)	−5 to +55	−10 to +45	−10 to +45
Bus voltage (V)	23 to 33	23 to 35	22 to 35
Input signal			
RF pulse width (μs)	102.4	102.4	102.4
PRF (Hz)	1020	1012	1020
RF duty cycle (%)	10.5	10.4	10.5
Level (dBm)	0 dBm (nom.)	−3 to +2	−1 to +2
Measured data			
Peak RF power output (dBm)	+43.3 to +43.5[1]	+43.8 to +44.6	+37.8 to +39.0
DC power consumption (W, max.)	71.7	24	10.4
Amplitude ripple across pulse (dB, p-p)	0.075	0.2	0.3
Phase ripple across pulse (deg, p-p)	1	4	8
Amplitude linearity with frequency (dB, p-p)	0.24	0.76	0.80
Phase linearity with frequency (deg, p-p)	2.8	8	9
Noise figure (dB, max.)	24	8.4	11
Size (cm)	36.8 × 16.5 × 11.4	30.0 × 18.8 × 9.1	20.3 × 15.7 × 13.5
Weight (kg)	5.3	5.0	2.8

[1]The TWTA operates in a CW or continuous mode; the RF input to the TWTA is pulsed.

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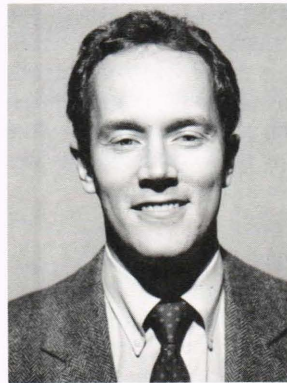
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