HIGH-POWERED, SOLID-STATE RF SYSTEMS*

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Abstract

Over the past two years, the requirement to supply megawatts of rf power for space-based applications at UHF and L-band frequencies has caused dramatic increases in silicon solid-state power capabilities in the frequency range from 10 to 3000 MHz. Radar and communications requirements have caused similar increases in gallium arsenide solid-state power capabilities in the frequency ranges from 3000 to 10000 MHz. This paper reviews the present state of the art for solid-state rf amplifiers for frequencies from 10 to 10000 MHz. Information regarding power levels, size, weight, and cost will be given. Technical specifications regarding phase and amplitude stability, efficiency, and system architecture will be discussed. Solid-state rf amplifier susceptibility to radiation damage will also be examined.

Introduction

For many years, semiconductors have been used as amplifiers of microwave energy. In the last few years, amplifiers have been built that use the combined output of many transistors to achieve power levels at frequencies between 10 and 3000 MHz, which are of interest to accelerator designers. In the frequency range between 3000 and 10000 MHz, significant strides are being made in semiconductor amplifiers; however, power levels are not yet high enough to be of practical value except as drivers for more conventional tube amplifiers.

The silicon bipolar transistor is the device of choice for amplification in the frequency range from 10 to 3000 MHz. Research is now being conducted on the silicon FET (Field Effect Transistor) and the silicon SIT (Static Induction Transistor). Whereas the bipolar device is primarily a pulse device, the latter two device configurations show promise of relatively high cw powers.

For frequencies above 3000 MHz, the GaAs (gallium arsenide) transistor is the solid-state device of choice. For power amplification, the GaAs transistor is usually built in a MESFET (MEtal-Semiconductor Field-Effect Transistor) configuration. GaAs is used at the higher frequencies because it has substantially higher electron mobility than silicon.

GaAs Amplifiers

Transistors made from GaAs can be used at frequencies above 3000 MHz because the mobility of the electrons is substantially higher (0.4 m²/v-s) than for silicon, which is 0.08 m²/v-s. Because of this parameter, amplifier transistors made from GaAs are commonly used at X-band (approximately 10000 MHz) and have been used at frequencies up to 60000 MHz.[1]

GaAs does not naturally occur in nature and is a difficult material from which to grow pure uniform crystals that can be sliced into 2- and 3-in.-diam wafers. In 1985 the combined wafer production of the U.S., Japan, and Germany was only 10000 wafers per week. As a result, GaAs transistors, which will deliver 1 W of output power at 10 GHz with a typical power gain of 7 to 8 dB for a single device, cost about $25.00 each in quantities of 1000. Devices have been made that deliver 10 W, but they are not generally available. Efficiencies are typically 20% with 30% being an upper limit of present technology. These are value-added efficiencies, which means that the gain of the device is taken into account when efficiency calculations are made.

One of the major limitations of GaAs is that it is a poor heat-conducting material. Silicon has a thermal conductivity of 1.5 W/cm-°C, whereas GaAs is three times as bad at 0.46 W/cm-°C. As a result, the gate channel of a GaAs transistor tends to heat rapidly, and the thermal problem is one of heat conduction from the gate channel. For reliable operation, the gate-channel temperature should not exceed 175°C. For this reason, pulsed operation does not enhance the power capability appreciably unless the device is run at a low duty cycle to enable the heat to be dissipated between pulses. Power ratings are typically quoted for cw operation. The best pulse power enhancement that can be expected is about 25%.

The typical GaAs device used for microwave amplification is a MESFET configuration. Figure 1 is a typical plan view and cross section of a MESFET.[2] It is beyond the scope of this paper to discuss the semiconductor physics of how such a device works. The interested reader is referred to one of several excellent texts on the subject.[2]
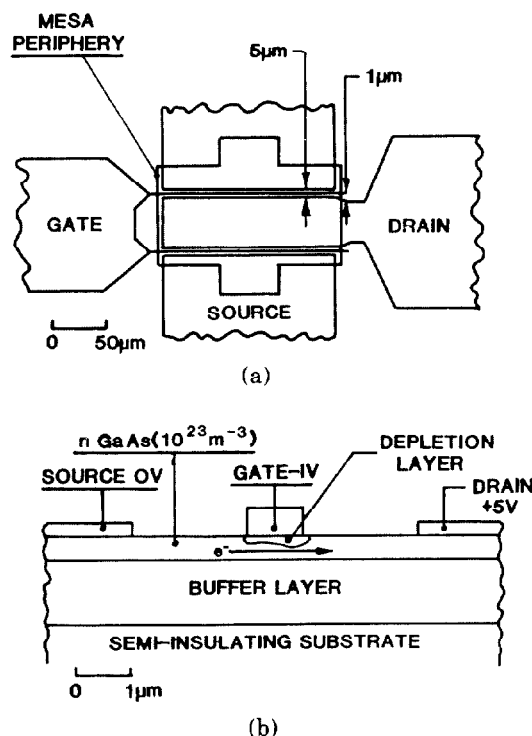

(a)

(b)

Fig. 1. GaAs MESFET
(a) Plan view. (b) Cross section.

At microwave frequencies, GaAs is a good substrate material. As a result, a great deal of effort is being expended on MMIC (Monolithic Microwave Integrated Circuit) research. This effort closely follows the work that has previously been done on LSI and VLSI for analog circuits. It is now conceivable to design an entire high-frequency amplifier or other functional circuit system on a single chip.

If GaAs transistors were readily available at 10 W per device at X-band, approximately 10^4 MESFETs would be required to build a 100-kW amplifier. Because megawatts of power are typically required to drive accelerators, it does not appear practical to consider GaAs MESFETs as viable amplifiers at the present time.

Silicon Transistor Amplifiers

Transistor amplifiers with power levels high enough to drive accelerator structures have been built in the last few years. One of these amplifiers was built for shipboard radar applications, operated at UHF frequencies, and had an output power of 250 kW.[3] Figure 2 shows a BEAR (Beam Experiments Aboard Rockets) amplifier specifically designed to drive an RFQ (radio-frequency quadrupole) at UHF.[4] The power is 60 kW peak, the pulse length is 60 μs, and the repetition rate is 5 pps. Two such amplifiers will be used to drive an RFQ.

This amplifier will not only be the first solid-state amplifier to drive an accelerator, it will also be the first

Fig. 2. BEAR rf amplifier.

amplifier with a significant power level to operate in space. It will be used in a ballistic trajectory rocket flight, hence the operational time will be short and the average power low. Because of the rocket-flight application, the amplifier was designed to be lightweight (1.1 g/W) and compact (7.1 W/cm³). Each amplifier operates from a 55-V battery pack.

Amplifiers using silicon bipolar transistors are readily available in the frequency ranges from less than 10 MHz to 1000 MHz at significant power levels. They are also available at frequencies up to 3000 MHz, but the power levels begin to decrease, as shown in Fig. 3. As the frequency increases, it is necessary to decrease the physical dimensions of the transistor to minimize the decrease in gain and eficiency. This decrease in active area causes a decrease in power capability.

The parameter that limits the output power from silicon transistors is the emitter-base junction temperature. For good reliability, this temperature should be kept below 120°C for silicon, although some manufacturers claim that their devices can be run up to 150°C.

A word of caution is appropriate about continuing to increase the power level per device by improving the heat-transfer characteristics of the package. The optimum voltage for a silicon transistor, because of internal breakdown characteristics, is 40 to 50 V. If a device is capable of a pulsed output power of 1 kW, the resulting device impedance is between 1.2 and 1.8 Ω. This low impedance makes it difficult to match the transistor to a 50-Ω system at a fixed frequency and almost impossible to match the transistor in an amplifier with any significant bandwidth. Thus, although there are no electrical limitations in the transistor itself, it becomes substantially more difficult to match the transistor to reasonable, external circuit impedances.

Any pulsed device can also be operated cw. Pulse lengths above 1 ms are considered the same as cw because the junction temperature reaches its peak value during the first several microseconds of the pulse and easily attains thermal equilibrium within the 1-ms time frame. In general, the pulse-power capability of a silicon bipolar transistor must be degraded by a factor of about 5 for cw operation, as clearly shown in Fig. 3. This derating is proportional to the rate at which the heat can be carried away from the junction. At UHF frequencies, the state of the art for a silicon bipolar transistor is 700 W at a few hundred microseconds pulse length. Collector efficiency (dc input to rf output) is 70% and power gain is about 9 dB.

The above figures are for a "single-ended" (one-transistor) device. A small package containing four transistors has been developed that has an output power at UHF frequencies of 2 kW peak.[5] This small package is shown in Fig. 4 and is 3.2 x 5.7 x 1.0 cm and weighs 28.3 g. "Dual-ended" (two-transistor) devices that operate push-pull are also available.

As previously indicated, two device types, the FET and the SIT, are being developed; they show promise of amplifying relatively high cw powers. In an FET-type device, the current flows vertically through the bulk of the device rather than through the surface, as in a bipolar transistor. The SIT is a class of short-channel JFETs, which, because it is a majority carrier device, can operate at relatively high voltages (80 to 100 V). It is also thermally stable, i.e., the electron mobility decreases with increasing temperature. This feature eliminates the necessity for ballast resistors typically used in bipolar
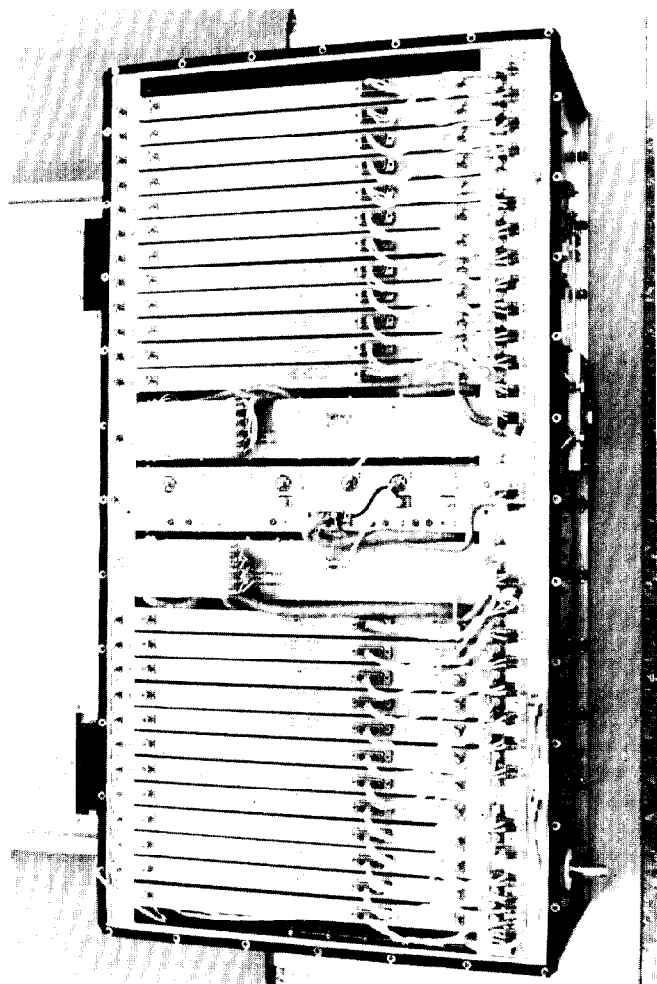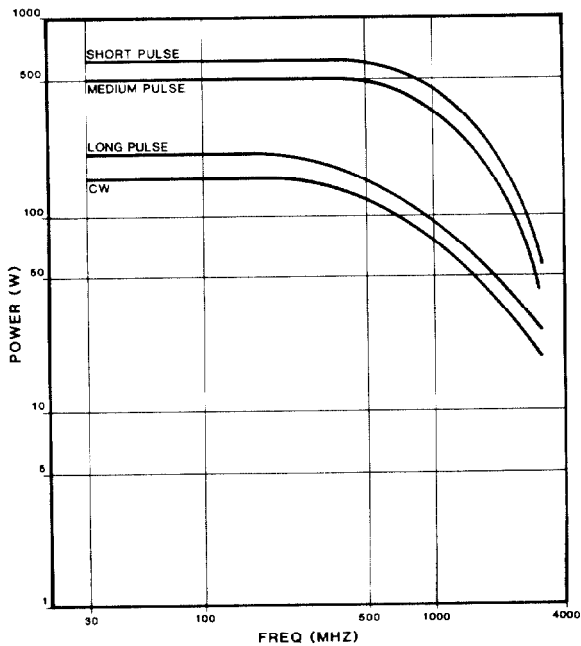
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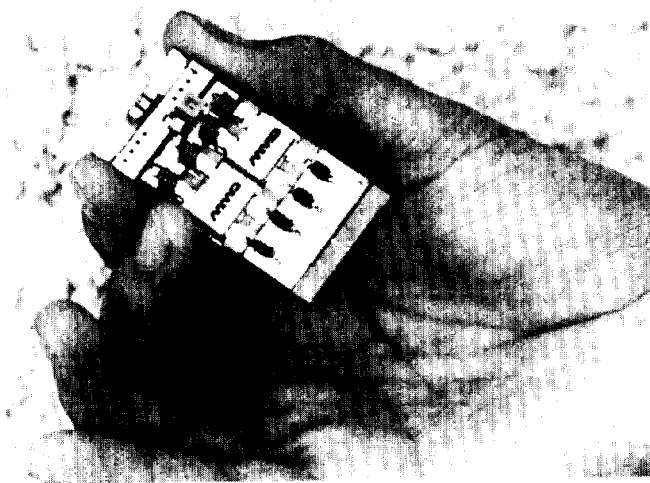Fig. 3. Output power vs frequency for silicon bipolar transistors.

Fig. 4. Four-transistor power module.

Fig. 5. Solid-state amplifier block diagram.

devices. These attributes, current flow through the bulk, high-voltage operation, and thermal stability, make the SIT a good candidate for a high-power, cw device.

Figure 5 is a block diagram of a typical solid-state amplifier. Six or seven stages of amplification are required for 60 dB of power gain. To operate stably, amplifier designers prefer to operate Class C, thereby running the devices well into saturation. The output power is controlled by splitting the amplifier into two identical halves, as shown, and then changing the relative phase between the two halves. When the two halves are in phase, the output power is maximum. To decrease the power, one amplifier section is dephased with respect to the other, and the excess power is dissipated in the final power combiner or reflected to the circulator in the power module. This amplitude control scheme has the disadvantage that amplifier efficiency suffers when the amplifier i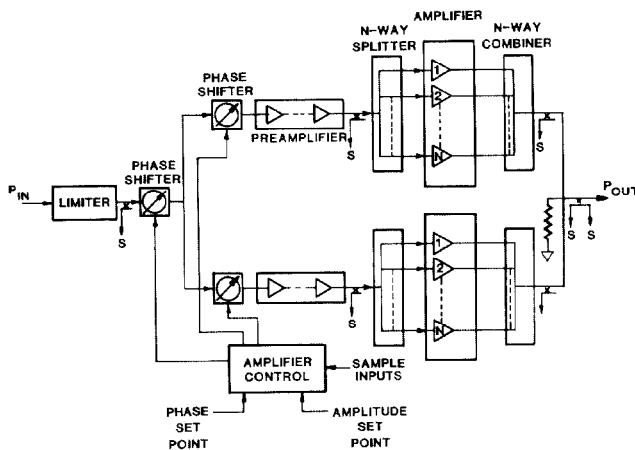s run at less than full power. To solve this problem, automatic switching of output power modules is being utilized. Fine tuning of the output is still done with the phase control between the two amplifier halves.

The amplifier shown in Fig. 2 was designed to be a "perfect" amplifier. It has internal power conditioning as well as phase and amplitude control. The amplitude control maintains power output to $\pm1\%$, and the phase control maintains phase shift through the amplifier to $\pm1°$. The phase and amplitude are set by an externally applied voltage. The response time for the internal control loops is 1 µs. Having this internal phase and amplitude control built into the amplifier makes the task of the accelerator control system designer much simpler.

Designing and building a high-power, solid-state amplifier requires the use of a number of power splitters and combiners. Amplifiers that have been designed and built, as well as those now in the design phase, use a variety of both these devices. Because the application as an accelerator driver is essentially fixed frequency, splitters and combiners can be designed with very little loss. Figure 6 shows a radial combiner driven by twenty-five 1.25-kW amplifiers for a total output power in excess of 30 kW. The total loss in the combiner is 0.7 dB. Figure 7 shows a 2.5-kW power module in which the
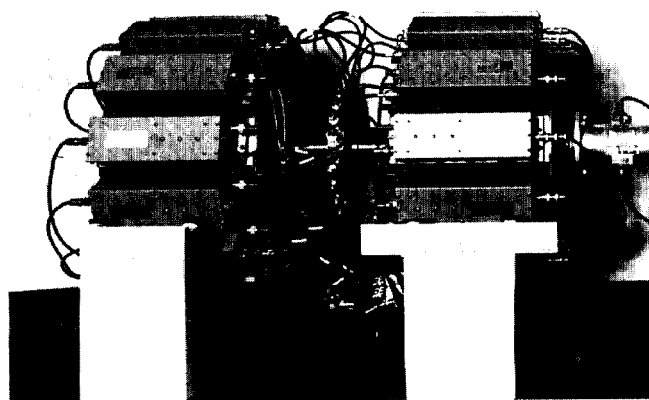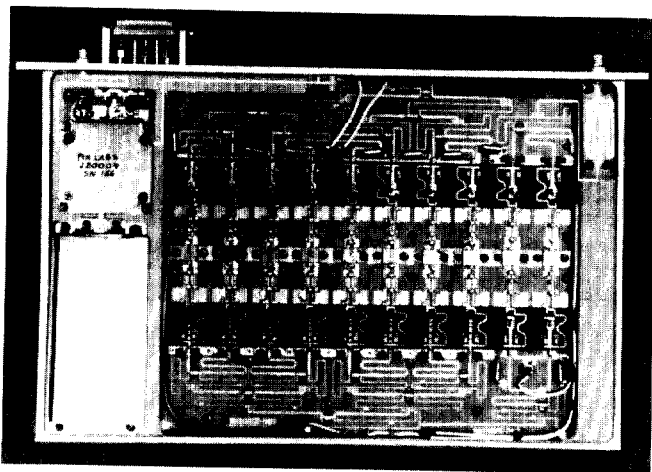

Fig. 6. Radial combiner.

Fig. 7. The 2.5-kW power module.

output of eight transistors is combined using a strip-line combiner. The drive power from the two preamplifier transistors on the board is also split eight ways using a strip-line splitter.

When an amplifier drives an accelerator cavity, the VSWR that the amplifier sees during the fill time is large. The energy that is stored in the cavity is also dumped into the amplifier at the end of the pulse. In a solid-state amplifier, unless other design provisions are made, this energy is dissipated in the transistor, thus further raising the junction temperature. Transistors are now being designed to operate a resonant load without protection, but the more conservative approach, which enables the designer to optimize other parameters of the amplifier, is to use a circulator. If one is designing for space applications, a transistor that does not require protection is attractive because the weight of the circulators can be avoided.

Solid-state devices are subject to radiation damage. A microwave transistor is purposely built with a narrow emitter-base junction that makes the solid-state devices inherently radiation hard. Radiation damage to solid-state devices does not cause sudden failure but rather a degradation in gain and efficiency beyond a certain threshold. Investigations[6] have shown that degradation of gain and efficiency will begin at an accumulated dose of about 10^{13} neutrons/cm^2 and 10^6 rad silicon of gamma. These two doses can be considered separately because the damage mechanisms are independent.

To date, all solid-state amplifier development work for accelerator rf power sources has been for space-based applications. As a result, there has been a great deal of emphasis placed on weight, volume, and rugged design. The design costs of pulsed amplifiers operating at 500 kW has been about $2.50/W. The cost of building and testing the amplifiers has been an additional $2.50/W for small numbers of amplifiers. Several caveats are necessary when using these figures, however. First, the figures quoted are for initial designs; subsequent designs should be cheaper because of previous experience. In addition, ordering many amplifiers of a given design will reduce the cost of building and testing. Second, the prices quoted are for a total, complete amplifier ready to plug into the power source. Installation time will be measured in hours. Third, the footprint of the complete system is small compared to a tube system of similar power levels, thus reducing the floor space required in a new facility.

Finally, the Navy's experience during the first several thousand hours of operation of solid-state amplifiers[7] has indicated that maintenance is essentially zero.

Conclusions

Solid-state amplifiers at frequencies and power levels of interest to accelerator designers have been and are being designed. The first such amplifier will be used to drive an RFQ next year. These amplifiers use many silicon bipolar transistors, which are combined to achieve the final power output. GaAs MESFET technology has not yet achieved individual device power levels that can supply, using a reasonable number of devices, the output rf power required by the typical accelerator structure. The future thrust of high-power, solid-state amplifiers will be toward more power per device with special emphasis on cw devices. Amplifier packaging, splitting, combining, power conditioning, and control system technology is in place. In order for solid-state amplifiers to be cost effective for a ground-based accelerator system, effort will have to be expended in the manufacturing processes for these devices.

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