Microfabricated next-generation millimeter-wave power amplifiers

A new approach to millimeter-wave power amplifiers offers significant advantages for military systems. The results of semiconductor manufacturing techniques are applied to Ka-band vacuum devices.

By Larry Sadwick, Jennifer Hwu and Dean Anderson

With the need for more band width and security, military communications systems are moving higher up on the spectrum scale. These systems are driving the need for higher-frequency amplifiers, especially in the Ka-band. Many Ka-band applications require more power than current solid-state power amplifiers (SSPAs) can provide. While conventional traveling wave tube (TWT) amplifiers (TWT-As) provide the frequency, power and reliability needed in such applications, they do not have the mass production advantages of today's solid-state devices. Novel microfabrication techniques blend the virtues of vacuum tubes with solid-state technologies to deliver higher performance from a compact package at cost-effective prices with much shorter lead times. The new fabrication method has affected the Ka-band power amplifier, and military applications can benefit from new power amplifier techniques.

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Applications

To update and upgrade the platform for the 21st century, U.S. government agencies, such as the Department of Defense, are planning to build communications systems in the frequency range well into the millimeter-wave region, i.e., the Ka-band surrounding 30 GHz. Millimeter waves offer a number of advantages over conventional C- and Ku- bands, including broader bandwidth, smaller antennas and greater security. The military is presently in the process of undergoing a system-wide transformation and upgrade of its communications systems from single-, dual- and/or tri-band (C-, X-, and Ku-band) to incorporate Ka-band into what is known as quad-band. In addition, a number of defense and military systems are in development—or are anticipated—at even higher frequencies. Military applications for millimeter-wave systems include high data rate network-centric communications and anti-jam and low detection/interception warfare communications.

Ka-band appears to be the likely choice for broadband gigabit wireless base stations providing broadband services (such as television and high-speed Internet and intranet access, data trunking, video conferencing, distance learning, tele-medicine and private data networks) to roof-mounted antennas on the homes of individual subscribers. It is believed that Ka-band will be the focus of efforts to develop high-speed satellite communications in a number of arenas.

Therefore, there clearly exists a need for Ka-band transmitters to address, among other things, these various and varied applications (expected power ranges from approximately 10 W to more than 200 W). These power levels at frequencies in the Ka-band and higher are presently outside the range that semiconductor electronics in the form of solid-state power amplifiers (i.e., monolithic microwave integrated circuits (MMICs)) can provide.

Vacuum electronics addresses these power levels in the millimeter-wave frequency range [1,2]. Some of the pertinent advantages and considerations of TWT vacuum electronics include:

- High efficiency (with multistage depressed collectors) [see sidebar]. DC to RF efficiencies of 30% to 70% are possible.

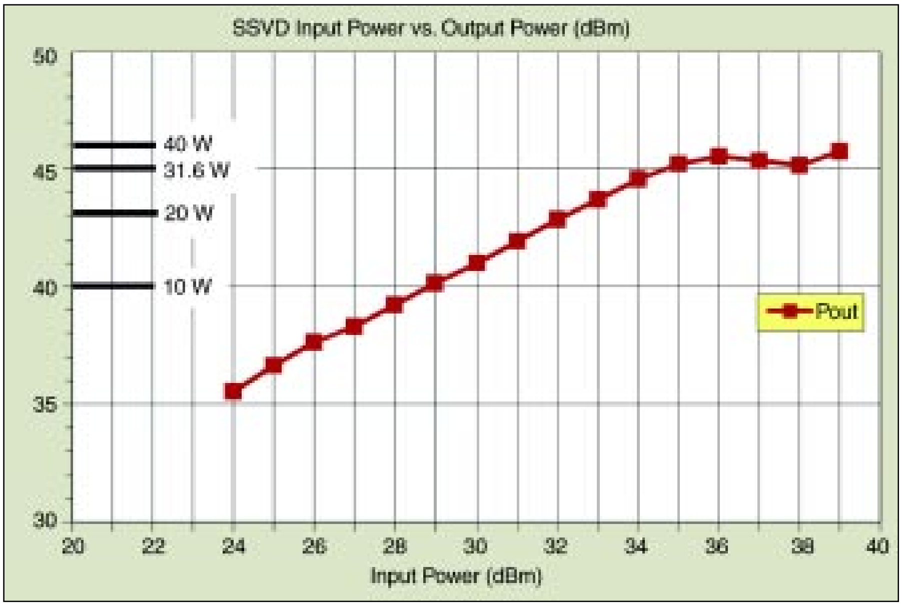

Figure 1. SSVD TWT amplifier prototype: a device designed to achieve, at 30.5 GHz, a power output of 10 W. This particular SSVD device saturates at 30 W.

Figure. 2. SSVD TWTA gain.

- Intrinsically radiation hard.
- High-temperature operation compared with SSPAs.
- Already used in many military and satellite applications for their efficiency, high frequency, high power capability, and reliability.
- In many cases, no solid-state alternatives exist.

Many, if not all, of the high-frequency, high-power requirements can be addressed by vacuum electronics. However, many of the fabrication techniques employed in the manufacturing of vacuum electronics tubes, such as traveling wave tubes, are not amenable or adaptable to high-volume production and suffer from low yield associated with the exacting machining tolerances required for millimeter-wave operation. The adoption of high-power millimeter-wave technology into many military and commercial communication systems has been relatively little because of the cost, availability and reproducibility of these high-power, millimeter-wave tubes. These difficulties of producing tubes for military (and, for that matter, commercial) use become even more significant for higher frequency millimeter-wave sources where the dimensions of the devices are being pushed to the limits of current conventional machining technology and beyond.

A solution is on the horizon

A solution to the millimeter-wave power amplifier/ source situation requires innovative approaches, methods and techniques.

Fortunately, this situation can be addressed by applying the same techniques that make possible the mass production of semiconductor electronics. In other words, this development work is based on the concept of the fabrication of vacuum electronics using semiconductor and micro-electromechanical systems (MEMS) microfabrication techniques and other high-volume manufacturing methods to realize affordable RF vacuum elec-

Power Supplies for Vacuum Electronics

Unlike power supplies designed for semiconductors that have direct current (DC) outputs of typically a few volts to dozens of volts, vacuum electronics typically use power supplies that have DC outputs measured in kilovolts. Vacuum electronics devices such as traveling wave tubes (TWTs) require negative high voltages. The high-voltage supplies are typically constructed using highly efficient switching power supply technology. The high-voltage power supplies come in various flavors, ranging from bare-bone units to extremely highly regulated supplies with a full complement of error detection, monitor and control circuitry (e.g., undervoltage, overvoltage, overcurrent, overtemperature, short circuits, arcing detection and protection) and power conditioning, including voltage sequencing. One metric of importance is the “stored energy” that is usually measured in units of joules. High-voltage power supplies designed for applications that require highly efficient systems and components usually have multiple voltage “taps” for use with multistage depressed collectors [please see other sidebar].

Efficiency of vacuum electronics

Vacuum electronics devices, such as TWTs, can be designed to be extremely efficient. This efficiency usually comes at the expense of increased complexity and cost by employing what is known as multistage depressed collectors. The simplest collector design scheme is to have the voltage of the collector be at ground potential since the cathode is at high negative potential. This simple scheme allows the collector to collect the spent electrons after the electrons pass through the RF interaction region and the electrons transfer some of their energy to the RF circuit. The major disadvantage of the simple scheme is that the energy of the spent electron beam can be significant. When the beam “hits” the collector, the kinetic energy of the beam is basically turned into wasted heat in the collector. This is detrimental in two ways: The first is reduced efficiency and the second is the need for either active or passive cooling of the collector to avoid excessive heating and temperature rise. Fortunately, the use of a depressed collector simultaneously increases the efficiency and reduces the amount of beam energy lost to heat in the collector.

The basic idea behind the single- or multi-stage depressed collector is to take the collector voltage from ground (zero) potential and “depress” the collector voltage to a negative voltage (single depressed collector) or set of negative voltages in a multidepressed collector. The trick is to not depress the collector voltage(s) so much that the electron beam is no longer attracted to the collector. With this stated, the electron still sees a relative positive potential between the cathode potential and the collector potential(s). However, the potential energy difference between the cathode and collector is now smaller and, hence, the electrons have less energy to be spent on heating the cathode. This reduction in spent electron beam energy conversion to heat is commonly referred to as recovering or reclaiming (to the power supply) part of the kinetic energy of the spent electron beam that would otherwise go to highly undesirable waste heat. Depressed collectors have led to a dramatic improvement in the efficiency of, for example, TWTs from approximately 10% DC to RF efficiency for single-stage standard collector to greater than 50% for a three-stage depressed collector—to greater than 60% for a properly designed four stage collector. With careful design and extensive simulation to accurately account for effects such as secondary electrons, back streaming of the primary electrons coupled with increased electron beam efficiencies has resulted in TWTs with DC to RF efficiencies approaching or greater than 70%. TWTs employed in on-board satellite space communications typically now have DC to RF efficiencies of more than 70%. Figure 3 illustrates the DC to RF efficiencies possible for the different collector schemes.

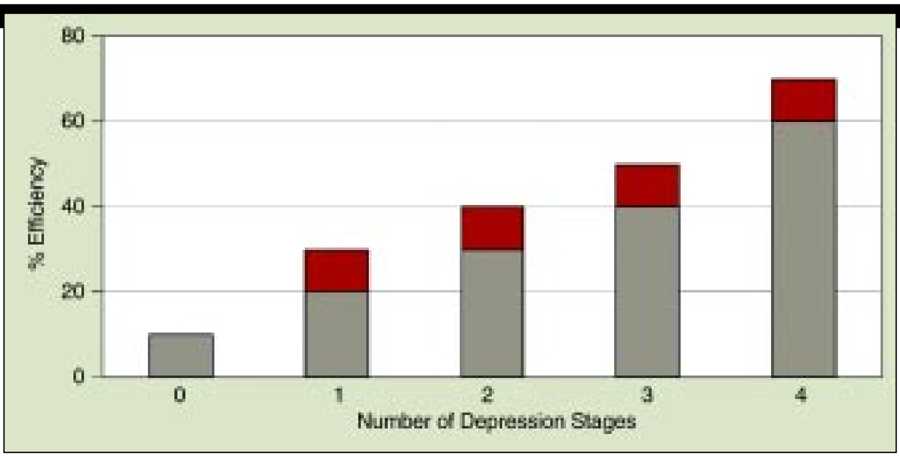

Figure 3. Simplified possible DC to RF efficiencies for various levels of multistage collector potential depression schemes.

tronics. For example, semiconductor microfabrication techniques are employed to produce multiple identical copies of the RF structure of the millimeter-wave amplifier. This has resulted in the successful development of a suitable high-power Ka-band amplifier using microfabrication techniques.

The techniques and methods used to manufacture these RF and MM power amplifiers are collectively referred to as solid-state vacuum device (SSVD) technology. The SSVD TWT-A is particularly suitable as a booster to a solid-state power amplifier (SSPA) to achieve a millimeter-wave power amplifier module (MMPM) [2] that fulfills, among other requirements, stringent power and gain demands of modern communication systems. MMPMs are a major advantage in a vast number of military applications and SSVDs are designed to exploit these advantages. Some of the pertinent advantages of SSVDs include:

- Manufactured using established semiconductor and solid-state micromanufacturing.
- Combine performance advantages of vacuum technology with mass production capabilities of solid-state microfabrication techniques.
- Use lower power SSPAs where they are cost-effective.
- Use vacuum devices where SSPAs leave off to provide boost to high power.
- Highly efficient DC to RF conversion using multistage depressed collectors.
- The capability to incorporate gain and compensation, phase shifting, and linearization circuits into the system.
- Simplified design provides increased reliability.
- More compact and lower weight than conventional TWTs.
- Devices can be created from S-band to W-band and beyond.
- CAD, simulation and microfabrication result in quick turnaround for new designs.

Based on microfabrication and other high-volume manufacturing methods, SSVD TWT amplifier prototypes have been successfully fabricated. An example of this is accomplishment is a device designed to achieve, at 30.5 GHz, a power output of 10 W. This particular SSVD device saturates at 30 W as shown in Figure 1.

Some of the design goals of this SSVD device family were:

- 30-31 GHz operation.

- > 50dB small signal gain.
- Output power range of 5 to 80 W.
- Compact size.

As also mentioned above, SSVDs combine TWT-A and SSPA advantages and more:

TWT-A advantages:

- High output power levels.
- Proven field robust performance.
- Efficient operation.
- Instantaneous broadband capability.
- Long life.
- Improved linearity with an optional linearizer.

SSPA advantages:

- Reduced manufacturing costs.
- Cost-effective at low power levels.

Furthermore:

- Compared to that for conventional TWTAs, SSVD fabrication is simplified for improved reliability.
- Compared to SSPAs, SSVDs dramatically reduce the cooling requirement and enable smaller, less expensive, and more reliable performance than any single RF power transistor technology.

As can be seen from Figure 2, this prototype power amplifier provides 11 to12 dB of linear gain. By incorporating its solid-state driver, the Ka-band MMPM can provide higher than 50 dB linear gain. The total SSVD prototype amplifier size is less than 4 inches x 2 inches x 1.75 inches and weighs less than 800 grams with further reduction in size and weight currently under way. The device mounts easily with its solid-state driver and associated bias protection circuit on a 6-inch x 8-inch base plate. Application-specific computer-aided design capability and tools were developed and used in the development of this SSVD TWT amplifier work. A close match between the simulation and experimental results was successfully achieved. This effort allows good theoretical guidance to the actual manufacturing and testing of the device and enables us to have fast device development turn around. Better gain (from the SSVD power amplifier alone), smaller size, and lighter weight are all being planned in the development of the next-generation device.

In addition to achieving high-power, high-frequency high-performance power sources, another goal of this work is to provide cost-effective and affordable microwave tubes with high reliability, employing microfabrication and other high-volume manufacturing techniques that are suitable for military and commercial communications systems. This development work also demonstrates the dramatic reduction in the parts and procedure steps for the manufacturing of the millimeter-wave source, taking advantage of, among other things, the precision and automation features offered by microfabrication techniques. In addition, there are significant issues that need to be taken into account, including the machining difficulty one faces with a millimeter-wave device due to its stringent dimension and tolerance requirements. As a result, cost analysis and reliability studies show a considerable cost reduction and an increase in reliability. Additional optimization of manufacturing procedures is ongoing, which will further enable these millimeter-wave devices to be produced in large quantities and at lower cost.

Reliability and lifetime

Contrary to the perception held by many—possibly based on historical data and hearsay—vacuum electronics' reliability can be high and lifetime long. Lifetime in conventional vacuum tubes such as TWTs is a strong function of the load and design of the tube.

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The reliability depends on the construction and manufacture of, in this case, the TWT. For example, properly designed, the lifetime of the thermionic cathodes used in conventional vacuum electronics can be hundreds of thousands of hours. In many cases, for high-frequency applications, the conventional tube lifetime exceeds that of the SSPA. The SSVD approach to TWT design leads to improved reliability by employing highly repeatable manufacturing processes and by reducing the parts count.

If implemented correctly, SSVDs offer an important advantage: the ability to shorten the turnaround time for custom design and manufacturing. While efforts are in progress to push the design to Ku and W bands, the technology has the potential to achieve TeraHertz frequencies.

Conclusion

In conclusion, a high-power Ka-band TWT-A has been successfully developed employing new manufacturing methods including using state-of-the-art semiconductor microfabrication to produce in parallel multiple identical copies of the RF structure of the millimeter-wave amplifier. The result of this work enables a new era in microwave electronics: one in which automated fabrication and assembly techniques developed for solid-state devices are used to build vacuum electronics capable of meeting future needs in millimeter and submillimeter transmitter systems. Because the dimensional accuracy of the microfabrication processes is on the order of one mm or less, devices based on this technology should reach multi-THz operating frequencies. Other RF interaction structures are also currently under development for applications ranging from Ku-band to W-band.

References

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