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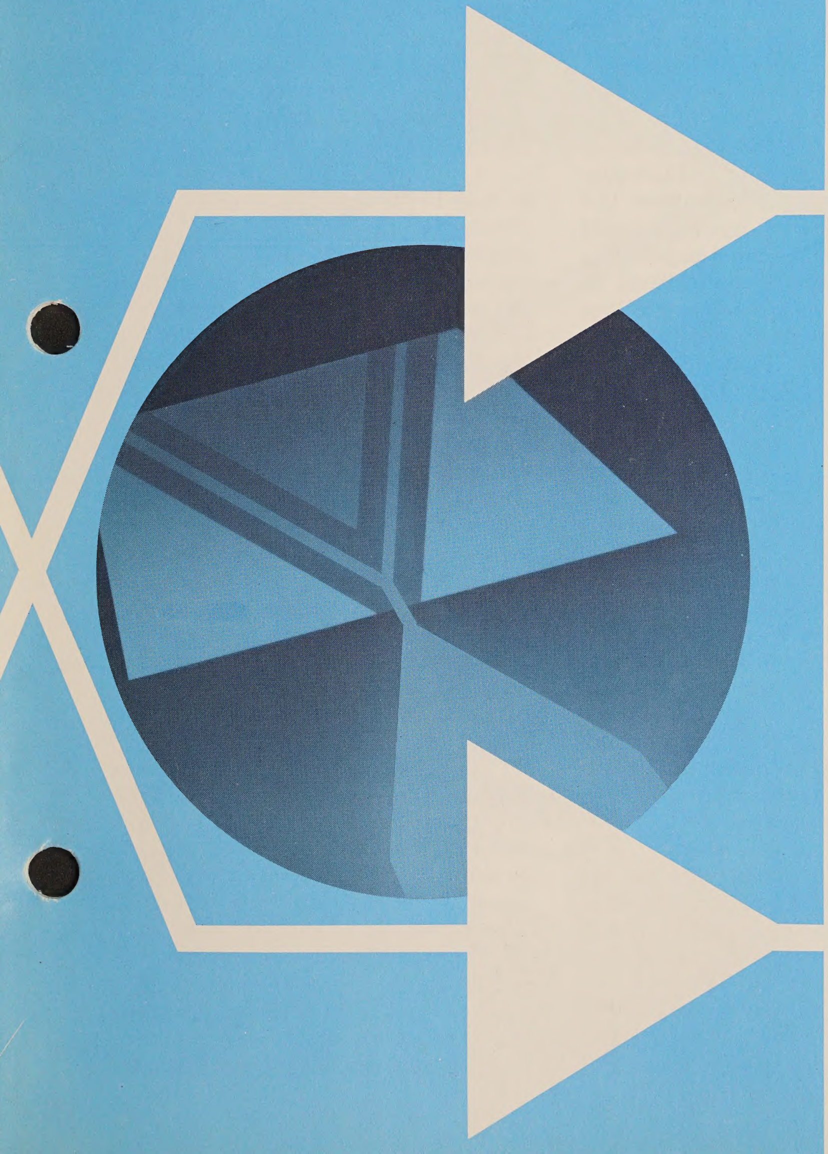
Low-Noise GaAs FET Amplifiers



WATKINS-JOHNSON COMPANY
Tech-notes

The field effect transistor (FET) is actually one of the oldest three-terminal, solid-state devices. It was proposed by William Shockley in 1952. Unfortunately, due to fabrication and technological problems, development of the FET as a practical device did not take place until the early 1960's. But, by this time, the silicon transistor had gained practically universal popularity due to earlier availability of useful devices. It was not until recent years that the FET was considered as a microwave device.

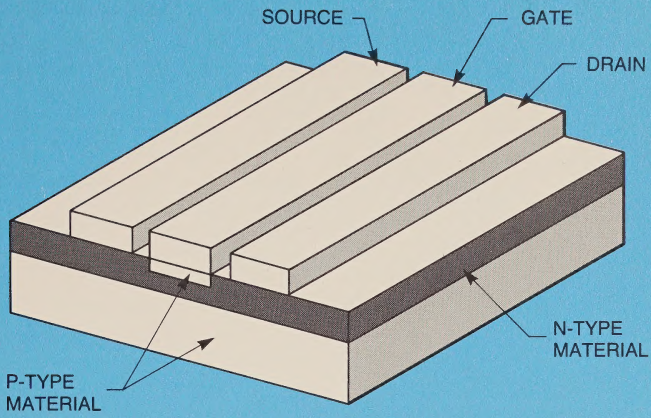
There are three types of FET's in use today, the simplest of which is the junction-FET (JFET), which came into use at about the same time as the first microwave silicon bipolar transistors. Further technological improvements in FET fabrication techniques led to the development of the metal-oxide-semiconductor FET (MOSFET), which is occasionally called an Insulated-Gate FET (IGFET) because of the oxide layer located between the gate and the substrate (see Figure 1). Neither the JFET or the MOSFET, however, could compete with the silicon bipolar transistor for microwave applications. It wasn't until the advent of the gallium arsenide metal-semiconductor field effect transistor (GaAs FET) that the FET came to be seriously considered for use in modern microwave technology.

A GaAs FET is a type of JFET, except that instead of a diffusion process at the pn junction, a Schottky barrier contact, which has a very short storage time, is utilized. In Schottky barriers, the current is conveyed by majority carriers, while in a pn junction it is carried by minority carriers. Whereas minority carriers limit the frequency response of the pn junction, the Schottky barrier has no such limitations, thus making it ideal for microwave applications.

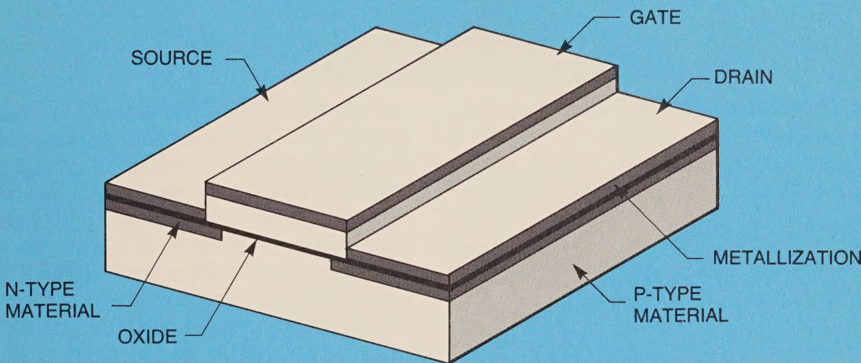
In the late 1960's, the first bipolar transistor amplifiers began to replace L- and S-band low noise TWT's. Progress in the development of broadband TWT replacement amplifiers, however, stopped at frequencies exceeding 5 GHz, around 1972. The low gain and high cost of these bipolar transistor amplifiers operating at frequencies higher than 5 GHz precluded their use except in specialized applications where power consumption for small size and weight made their use imperative. Higher frequency amplifiers made their debut with the commercial availability of the gallium arsenide FET. The first C-band transistor amplifier to replace existing TWT's in a military system was introduced in 1974.

In mid-1975, the first commercially available X-band (8-12 GHz) amplifier was introduced. Today, extended X-band coverage (7-14 GHz) and waveguide bandwidth coverage to 18 GHz is available, and research in the 18-26 GHz range is being conducted. Narrowband coverage with low noise figures is allowing GaAs FET amplifiers to replace expensive and cumbersome parametric amplifiers in radar and communications applications.

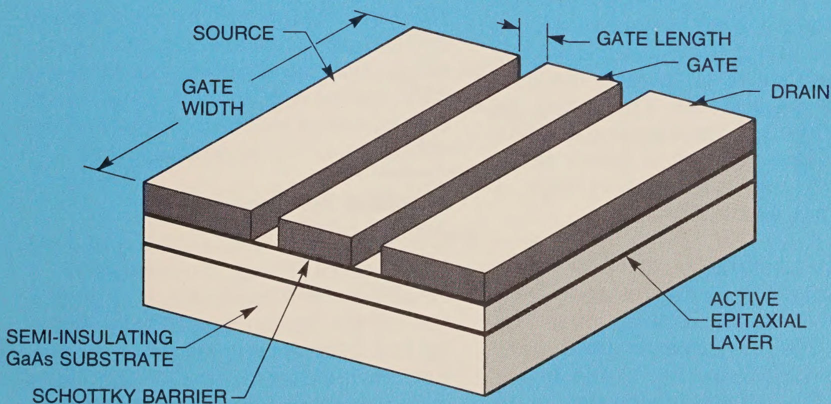
Some of the advantages of the GaAs FET amplifiers which are attracting the attention of equipment users include better rf performance in the form of lower noise figures and higher output powers, as well as longer MTBF and lower costs than low-noise TWT, parametric, and tunnel diode amplifiers. While much of microwave GaAs FET technology has been heavily slanted in the direction of amplifier development, recently there have also been advances utilizing GaAs FET's in microwave oscillators. Although this technology is still quite new, it is possible that GaAs FET's will eventually supplant some frequency sources in the X, Ku, and even higher bands.



JUNCTION-FET (JFET)



METAL-OXIDE-SEMICONDUCTOR-FET (MOSFET)



METAL SEMICONDUCTOR-FET (GaAs FET)

Figure 1. There are three basic types of FET's.

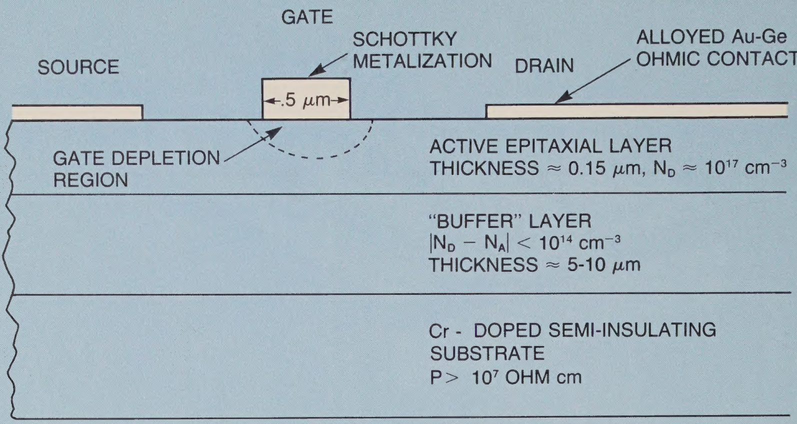


Figure 2. Basic structure of a GaAs FET with 0.5 micron gate.

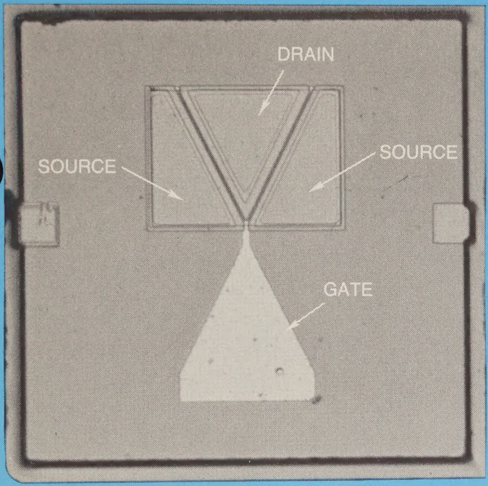
Gallium Arsenide Field Effect Transistors

The basic structure of a typical GaAs FET used in microwave amplifier applications is shown in Figure 2. The actual appearance of two GaAs FET's from different manufacturers is shown in Figure 3. The major terminals of the FET are the source, drain and gate. The current carriers, electrons in the case of microwave GaAs FET's, flow from the source to the drain when a bias is applied to the terminals. A negative potential on the gate electrode thus controls the current flow in the device. This change in current flow is proportional to the gate signal. Since very little power is required to vary the gate voltage, a power gain is possible.

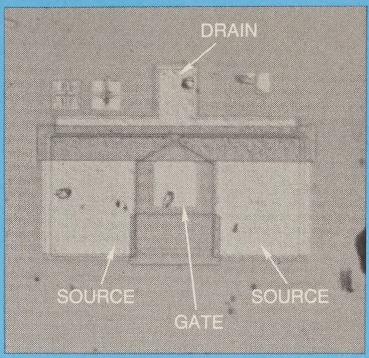
One of the critical dimensions in GaAs FET technology is the distance from the source to the drain, since the smaller this dimension is, the higher the operating frequency of the device may be. The noise figure is also lower at a given frequency as the gate length becomes smaller. In general, the length of the gate structure for the C- and X-band GaAs FET's is one micron; those used in Ku band have a one-half micron gate length. Power GaAs FET's have the same gate length but have a much larger gate width. (The gate length is in the direction of carrier travel, while the gate width is in the transverse direction.) To put into perspective the difficulty involved in producing devices with such tiny dimensions as one-half micron, it should be noted that the human hair has a width of about 75 microns and the period at the end of this sentence has a diameter of around 500 microns. Besides gate length, other critical dimensions in GaAs FET technology include gate width, distance from source to drain, and the thickness of the epitaxial layer.

Amplifier Performance

Economically, the choice between bipolar transistor and GaAs FET amplifiers will normally give preference to the bipolar type at frequencies up to 2 GHz. A comparison of the performance between bipolar and GaAs FET transistor amplifiers at frequencies below 2 GHz gives the FET amplifier only a slight edge—about 0.2 to 0.3 dB lower noise figure, but microwave matching networks for FET's are very difficult to achieve at



NEC



DEXCEL

Figure 3. Basic structure of GaAs FET's from different manufacturers.

these frequencies. Above 2 GHz, however, the performance of the GaAs FET amplifier exceeds that of the bipolar amplifier. In the 2-4 GHz range, noise figures can be 2.5 dB for the GaAs FET amplifier compared with 4 dB for the bipolar transistor amplifier—a difference which can be of critical importance in many applications. The improved gain per stage and the 2 dB noise figure of the GaAs FET amplifier makes its use as a parametric amplifier replacement a practical possibility. At frequencies above 4 GHz, bipolar transistor performance begins to degrade sharply, while microwave amplifiers utilizing GaAs FET devices can be built to operate at frequencies above 18 GHz. For example, broadband GaAs FET amplifiers with noise figures of less than 7.0 dB have been built to operate at frequencies to 18 GHz (see Figure 4).

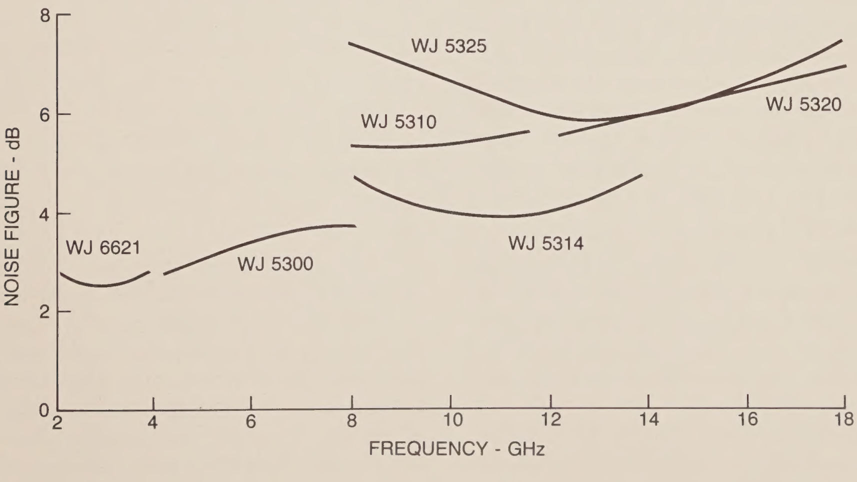


Figure 4. Noise figure of W-J FET broadband amplifiers.

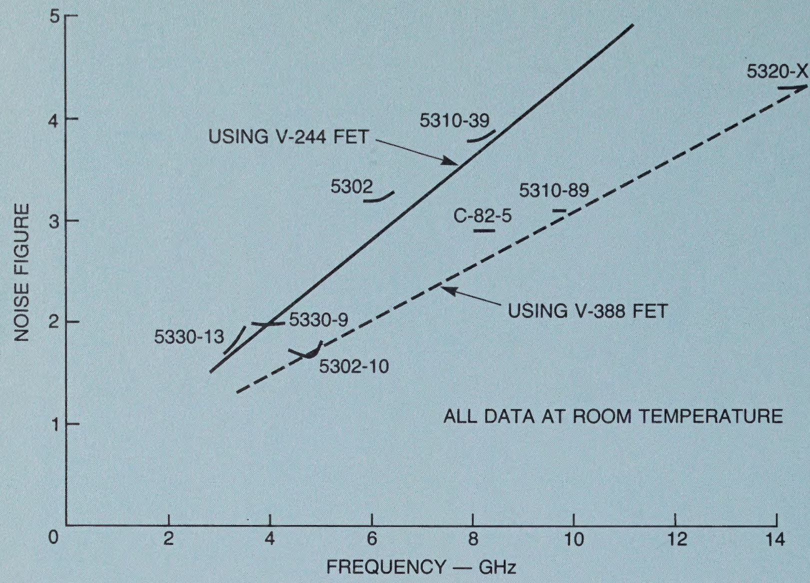


Figure 5. Noise figure of narrowband W-J FET amplifiers.

Figure 5 shows the performance figures for narrowband amplifiers.

Another advantage of the GaAs FET is the generally wide dynamic range which the device exhibits when compared to the ultra-low noise silicon transistor at lower microwave frequencies. Wideband GaAs FET amplifiers with noise figures below 2.0 dB and only 15 dB gain have been built to operate in the 3.7-4.2 GHz region with 10-dBm power capability. This high dynamic range is superior to other low-noise amplifier technology such as TDA's (tunnel diode amplifiers) and parametric amplifiers. For example, a typical 7-GHz GaAs FET amplifier with a 25-dB gain will have a noise figure of 4 dB and a third-order intercept point of 20 dBm for a spurious, free dynamic range of 70 dB. A TDA with similar noise figure and gain will have an intercept point of 0 dBm and a corresponding dynamic range of 57 dB. As a result, GaAs FET amplifiers are becoming widely used in communications applications.

The wide band performance of GaAs FET amplifiers presently exceeds that of competing technologies with performance frequencies to 18 GHz. A typical example of data for an octave bandwidth, I-, J-band amplifier is shown in Figure 6. The clear advantage of the wide dynamic range of this low noise, low gain amplifier results from the characteristic of the FET and the modular gain design concept used in the amplifier.

The modular gain concept for the FET amplifiers produced at Watkins-Johnson allows the amplifier to be built from several identical amplifier stages operating in cascade. The modules typically have 7 dB to 10 dB gain; the example above uses three 7-dB gain modules. Higher gain amplifiers can be made simply by using more modules. This concept of design allows the manufacture of a large number of identical stages which are assembled into specific amplifiers as required to fulfill customer requirements. The key to this design approach is the use of the balanced amplifier which is described later.

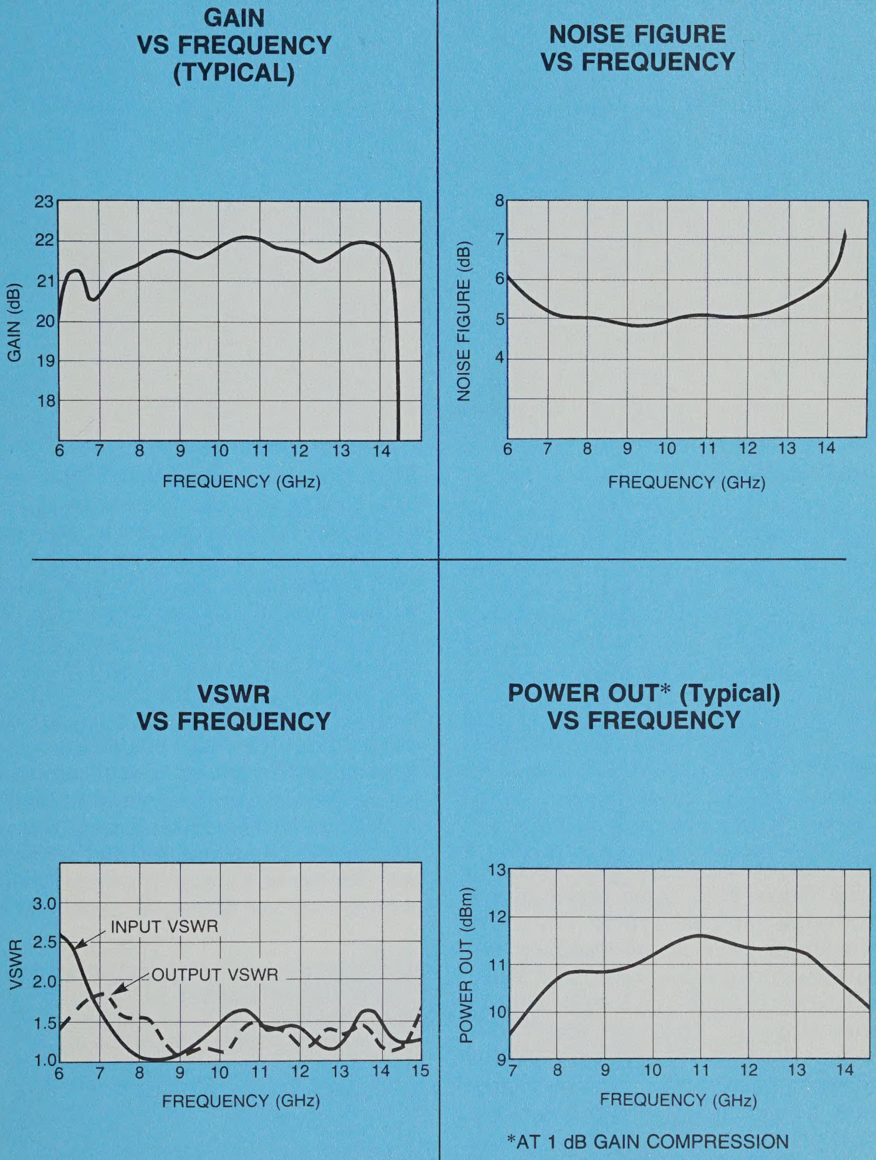


Figure 6. Typical small-signal performance of a 21-dB gain amplifier.

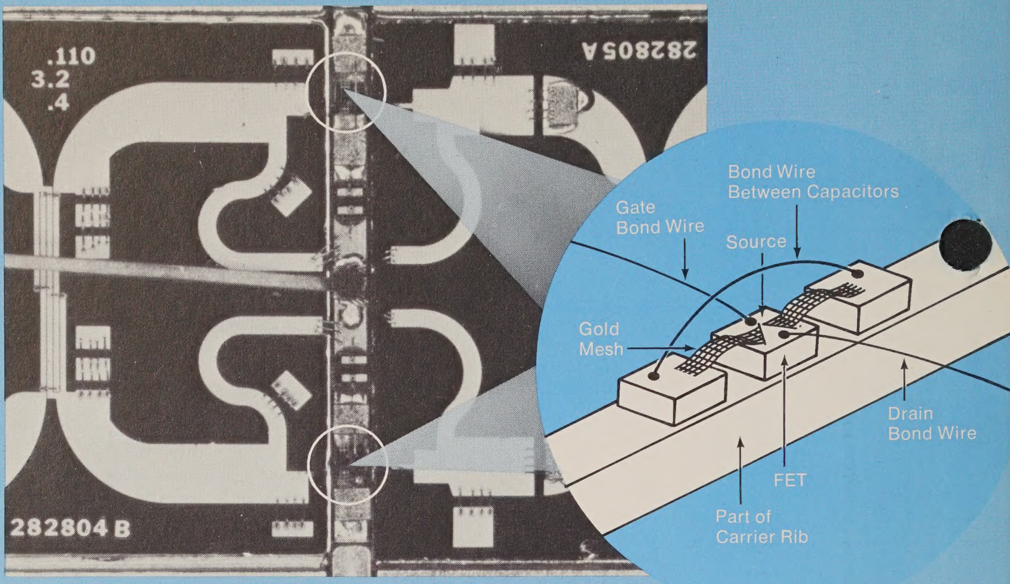


Figure 7. Intricate gold-to-gold bonds must be made to the source, gate, and drain pads of the GaAs FET.

Circuit Assembly

To achieve maximum rf performance from a GaAs FET, the designs utilized by Watkins-Johnson attach the chip itself to the circuitry rather than using the FET in a protective package (see Figure 7). The entire amplifier is then sealed in a hermetic case which provides the protective ambient for the circuits and transistors.

Fabrication of amplifier modules using GaAs FET chips represents a challenge for the hybrid assembly techniques used in assembling microwave integrated circuits. Since gallium arsenide is mechanically more fragile than silicon (the material used for microwave bipolar transistors), greater care must be exercised in its handling. Also, because of its extremely small electrical dimensions, static discharges and electrical transients occurring during assembly can cause catastrophic device failure. Special tooling has been developed at Watkins-Johnson to perform device-circuit assembly that gives high yields.

After the chip is attached to the circuit, electrical contacts must be made to the source, gate and drain pads on the chip's top surface. The drain and gate bonds are made with gold wire with a diameter of approximately 20 microns (0.0007 inch). The pads on the chip and substrate are also gold so that the contacts are highly reliable gold-to-gold bonds. The source connections use gold mesh instead of a single wire to provide the lowest possible inductance. The source-to-ground connection must be low inductance so that the upper frequency limit of the amplifier is as high as possible. These connections are shown in Figure 7.

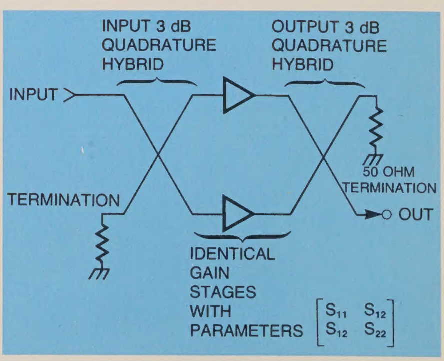
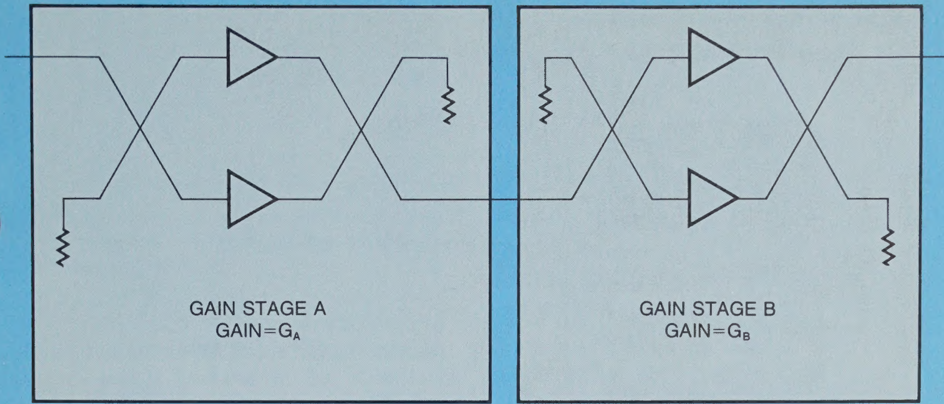


Figure 8. Balanced amplifier stage.



$$S_A = \begin{bmatrix} S_{11A} & S_{12A} \\ S_{21A} & S_{22A} \end{bmatrix} \qquad S_B = \begin{bmatrix} S_{11B} & S_{12B} \\ S_{21B} & S_{22B} \end{bmatrix}$$

$$\begin{aligned} \text{GAIN} &= 20 \text{ LOG } S_{21T} = 20 \text{ LOG } S_{21A} + 20 \text{ LOG } S_{21B} + 20 \text{ LOG}(1 \pm S_{22A} S_{11B}) \\ &= G_A + G_B \pm M, \text{ where } M = 20 \log (1 \pm |S_{11B} S_{22A}|) \end{aligned}$$

Figure 9. Gain of two cascaded balanced gain stages.

Balanced Amplifier

Fundamental to broadband, solid-state amplifiers is the balanced amplifier concept introduced by R. Englebrecht in early 1964. Figure 8 shows a balanced amplifier stage consisting of two identical single-ended gain stages (including input and output matching circuits) connected by two 3-dB quadrature hybrids.

The greatest advantage of connecting two identical gain stages with quadrature hybrids is that a perfect match is provided at the input and output regardless of the input and output impedances of the individual amplifier stages, providing the stages are identical. This allows acquisition of the desired gain without danger of interaction between the various amplifier stages (see Figure 9). Modular construction, which is characteristic of the Watkins-Johnson GaAs FET amplifier, allows a quick and simple tuning procedure to meet specific performance goals. Additionally, the balanced amplifier stage provides a 3-dB increase in output power over the single-ended type of design because it combines the power of 2 devices. Figure 10 shows a photograph of an X-Band amplifier constructed of several balanced amplifier stages.

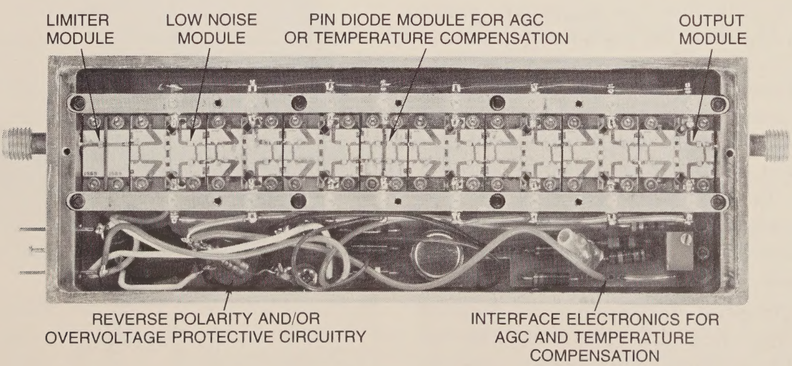


Figure 10. X-Band amplifier with cascaded balanced amplifier stages.

Applications

GaAs FET amplifiers are presently being used in nearly every microwave system application. Wide-band amplifiers are being used in such diverse fields as reconnaissance receivers, deceptive ECM receivers and jammers, and direction finding (DF) receivers. Narrow band amplifiers are used in satellite and earth station receivers, line-of-sight microwave repeaters, and radar receivers.

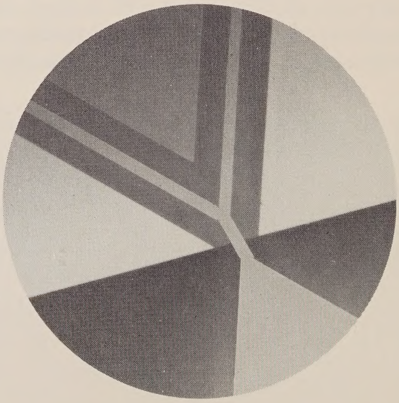
In some receiver locations, the antenna is often remotely located from the receiver, thus requiring the use of an amplifier as a line driver. This situation requires the placement of the amplifier in close proximity to the antenna to overcome the insertion loss of the connecting cable or waveguide. The line driver establishes the system noise figure by providing sufficient gain to cover the cable loss. The GaAs FET amplifier is ideal for this application because its high dynamic range capability with modular gain increments does not affect the receiver dynamic range.

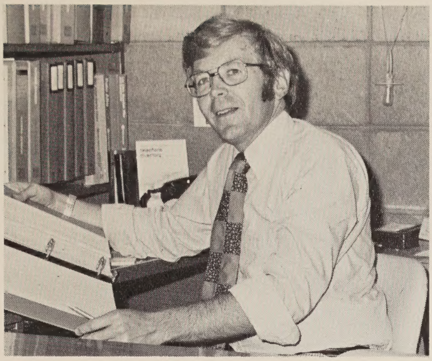
A second major advantage of the GaAs FET amplifier is low cost. As the manufacturers of the devices have gained experience, the cost of the transistors has followed the traditional declining price curve of semiconductor devices. This has allowed the cost of the GaAs FET amplifiers to be reduced correspondingly. The use of the balanced amplifier modular approach described above simplifies the alignment procedure required for such components.

To date, microwave communications has been a relatively sophisticated and costly technology. However, the advent of the low-cost, GaAs FET amplifier, coupled with new antenna technology, has led to dramatic cost reductions for communication terminals. Future costs of this type of equipment will be in for a substantial decline leading to more widespread usage in satellite communication networks.

A third benefit of the GaAs FET amplifier is the construction simplicity. This feature, as well as low cost, leads to lightweight and rugged amplifiers for military usage. Improved reliability and system performance result in air and ship radar applications as well as in missile guidance systems.

The present GaAs FET amplifier technology is mainly limited to low noise, small-signal devices. Power outputs of practical broadband amplifiers range from 10 mW to 100 mW, although research is being conducted to develop devices capable of greater output powers. Compared to TWT amplifiers used for similar functions, the power output and noise figure combination of GaAs FET amplifiers offer better electrical performance. However, the power capability of the TWT is unchallenged. GaAs FET amplifiers are now replacing the TWT, tunnel diode, and parametric amplifier in low-noise applications up to 18 GHz. As the device capability improves, it is expected that GaAs FET amplifiers will replace tubes with higher power capability. It is expected that one watt power capabilities will be available within the next two years.





Frank E. Emery

Dr. Emery is manager of Watkins-Johnson's Microwave Integrated Circuits Department. He is responsible for various programs involving transistor amplifiers for low-noise and medium-power applications, as well as Microwave Integrated Circuit (MIC) subassemblies. Dr. Emery's department is currently involved in the development of cooled, low-noise amplifiers for communications and radar applications, bipolar and GaAs FET transistor amplifiers, special-purpose frequency memory loop amplifiers, and high-reliability amplifier development and production for spaceflight applications. Before becoming manager of the MIC department, Dr. Emery was Head of the YIG Device Engineering Department in Watkins-Johnson's Solid State Division, where he was in charge of developing 26-40 GHz GaAs oscillators and the first X-band oscillator utilizing a GaAs FET.

Besides the numerous publications to his credit, Dr. Emery also holds patents on a solid-state traveling wave amplifier and a microwave transistor package. Dr. Emery received a B.A., B.S.E.E., M.S., and Ph.D from Rice University, Houston, Texas.

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