the assembly of the unit. The circuit can be etched only on one board and the necessary connection in the center of the configuration can be made by soldering a small strip of copper between the desired points. If such a modification is made, it may be necessary to use a thicker layer of copper or a narrower coupling gap in order to maintain the same effective coupling across the gap.

Conclusion

A printed-circuit strip transmission line hybrid junction with input voltage standing-wave ratio less than 1.26 (2 db) over ±20 per cent band, power division within 0.1 db, and isolation of the two pairs of the conjugate ports greater than 24 db and 40 db has been developed for the UHF band. Circuits have been fabricated which operate satisfactorily up to 1500 mc. These hybrid junction circuits have many useful applications and can easily be reproduced if a few precautions are taken in the etching and assembly of the circuit.

Acknowledgment

The author gratefully acknowledges the many discussions and helpful suggestions by W. W. Mumford on the subject of hybrid junctions. Appreciation also goes to W. H. Conway for his help in the course of this investigation.

Gallium-Arsenide Point-Contact Diodes*

W. M. SHARPLESS†, FELLOW, IRE

Summary—**This paper describes some of the work on gallium-arsenide point-contact diodes which is currently in progress at the Bell Telephone Laboratories, Holmdel, N. J. Gallium arsenide, one of the Group III–V intermetallic compounds, possesses properties which tend to make it superior to either silicon or germanium for many high-frequency diode applications. By controlling the resistivity of the gallium arsenide and the point-contact processing techniques, diodes have been fabricated specifically for use as millimeter wave first detectors, high-speed switches, and reactive elements for microwave parametric oscillators and amplifiers. The operating characteristics of several different types of gallium-arsenide reactive diodes are discussed and mention is made of simple design formulas which may be used to tentatively evaluate the performance to be expected from such diodes. Noise figure measurements are included in a résumé covering some of the experimental results that have been obtained using gallium-arsenide point-contact diodes as variable reactance elements in microwave parametric amplifiers.**

Introduction

Gallium arsenide, one of the Group III–V intermetallic compounds, possesses properties which tend to make it superior to either silicon or germanium for many high-frequency diode applications. By controlling the resistivity of the gallium arsenide and using the proper processing techniques, point-contact diodes have been fabricated specifically for use as millimeter wave first detectors, high-speed switches, or reactive elements for microwave parametric oscillators and amplifiers.[1–6] The important operating characteristics of different types of experimental gallium-arsenide varactor diodes will be discussed in this paper, and mention is made of the general fabrication methods employed in assembling the diodes.

* Received by the PGMTT, August 8, 1960.
† Bell Telephone Labs., Inc., Holmdel, N. J.

Materials

All the single-crystal gallium-arsenide (GaAs) material used in this work was prepared by J. M. Whelan, Bell Telephone Laboratories, Murray Hill, N. J. Purified material was doped to the required resistivity by regrowing the crystals in an arsenic atmosphere containing donor impurities such as sulphur, selenium, or tellurium. In order to realize the full electron mobility of the GaAs, efforts were made to avoid compensated doping. The final single crystal N-type material was sliced into thin disks, given a back contact of deposited

[1] W. M. Sharpless, "High frequency gallium arsenide point contact rectifiers," *Bell Sys. Tech. J.*, vol. 38, pp. 259–270; January, 1959.
[2] B. C. DeLoach and W. M. Sharpless, "An X-band parametric amplifier," Proc. IRE, vol. 47, pp. 1664–1665; September, 1959.
[3] M. Uenohara and W. M. Sharpless, "An extremely low noise 6-kMc parametric amplifier using gallium arsenide point contact diodes," Proc. IRE, vol. 47, pp. 2113–2114; December, 1959.
[4] B. C. DeLoach and W. M. Sharpless, "X-Band parametric amplifier noise figures," Proc. IRE, vol. 47, pp. 2114–2115; December, 1959.
[5] B. C. DeLoach, "17.35 and 30 kMc parametric amplifiers," Proc. IRE, vol. 48, p. 1323; July, 1960.
[6] W. M. Goodall and A. F. Dietrich, "A fractional millimicrosecond electrical stroboscope," Proc. IRE, vol. 48, pp. 1591–1594; September, 1960.

tin followed by a nickel plate forming a surface suitable for soldering. The material was then ultrasonically cut into 0.028-inch disks suitable for mounting in the miniature cartridge used in making the diodes. The point-contact surface was given a mirror-like finish and, immediately before setting up the diodes, the polished surface was given a light etch with a dilute solution of hydrofluoric and nitric acids.

The point-contact springs were made of phosphor-bronze wires having a diameter of from one to three mils, depending on the type of diode being assembled. In all cases, the ends of the springs were sharply pointed electrolytically to a radius of about one-tenth mil in a dilute solution of sulfuric acid.

The miniature cartridge-type case in which the GaAs diodes are mounted is shown in Fig. 1. The small GaAs disk and the phosphor-bronze point-contact spring are shown mounted on the ends of round nickel rods which are pressed into place from opposite ends of a round steel-capped quartz-insulated cartridge type holder. The use of a section of fused-quartz, thin-wall tubing provides a low-loss, low-capacity insulating section which is mechanically relatively insensitive to temperature changes.

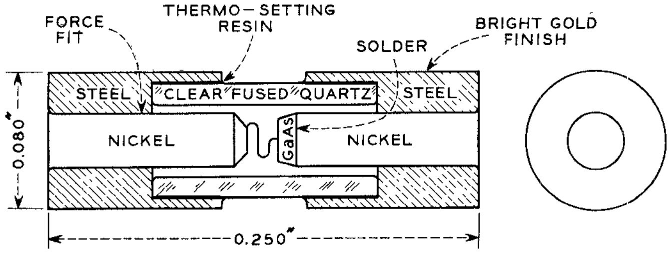


Fig. 1—Sectional view of the cartridge-type point-contact diode.

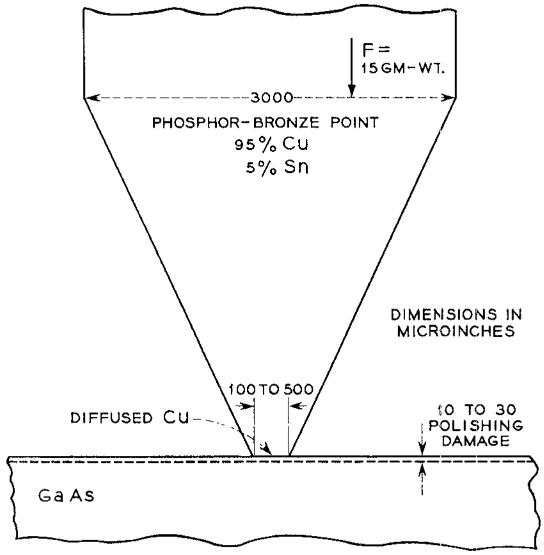


Fig. 2—Expanded view of the point-contact area (courtesy N. C. Vanderwal).

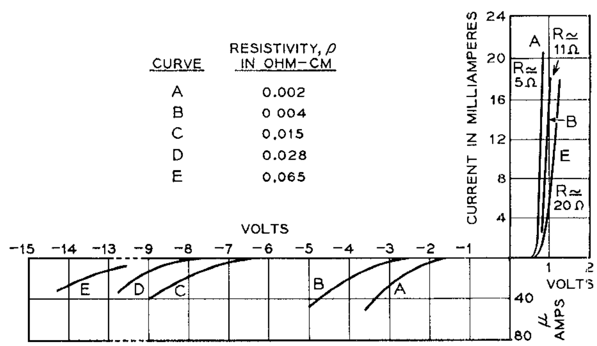


Fig. 3—Static characteristics of N-type gallium-arsenide point-contact diodes.

Forming Techniques

After contact is established between the point-contact wire and the polished surface of the GaAs, the point contact is electrically formed by applying a low ac voltage directly on the diode terminals. Because of the fact that the reverse impedance of these diodes is very high, most of the forming current flows in 60-cycle pulses in the forward direction. Depending upon the type of diode being formed, the peak currents are limited by the use of an appropriately sized series resistor. The static characteristic of the diode is displayed on a cathode-ray oscilloscope while the forming is in progress.

Fig. 2 shows an enlargement of the point-contact region of the diode. During the forming process, a high current density is produced at the point which heats the small point-contact area. It is believed that this allows a small amount of copper (an acceptor in GaAs) to diffuse from the phosphor-bronze point (95 per cent Cu+5 per cent Sn) into the GaAs. The surface damage incurred during polishing probably enhances the rate of diffusion. This diffusion process forms a tiny, extremely abrupt junction which we desire for efficient operation at very high frequencies.

Diode Characteristics

The effect of varying the resistivity of the GaAs material used in the point-contact diodes is shown in Fig. 3. Typical static characteristics are shown for diodes made from N-type doped GaAs materials, ranging from 0.065 ohm-cm for a lightly doped sample to 0.002 ohm-cm for heavily doped material. It should be noted that the heaviest doped material yields the lowest diode forward resistance (about 5 ohms for $\rho=0.002$ ohm-cm material). However, as we will see later, the capacity of the diode increases with the doping, so that a compromise must be made between lower spreading resistance and higher capacitances; for a given parametric amplifier application, the doping is usually chosen to give the highest cutoff frequency.

To illustrate this point, Figs. 4 and 5 show the measured voltage-current and voltage-capacitance charac-

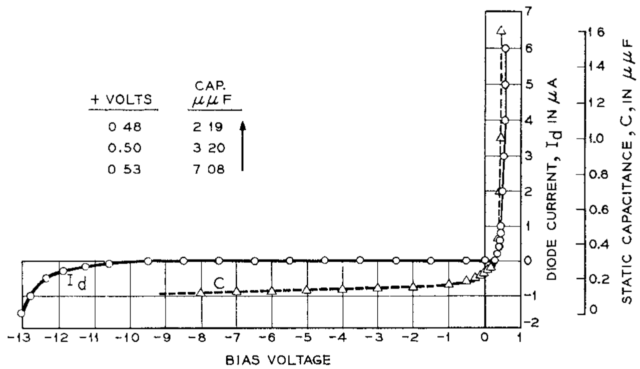


Fig. 4—Voltage-current and voltage-capacitance characteristics of a typical point contact GaAs diode ($\rho = 0.025$ ohm-cm).

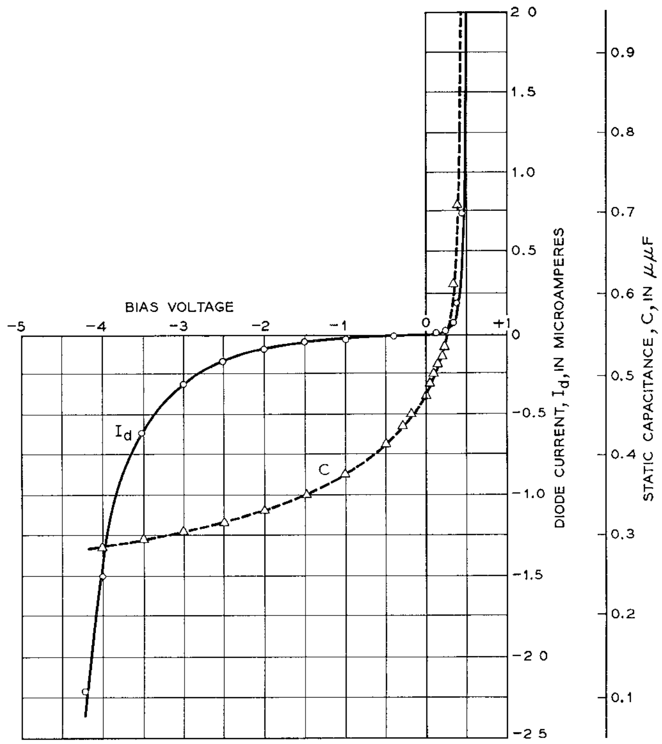


Fig. 5—Voltage-current and voltage-capacitance characteristics of a typical point-contact GaAs diode ($\rho = 0.003$ ohm-cm).

teristics of two typical point-contact types of GaAs experimental diodes. Fig. 4 shows the curves for a diode made with 0.025-ohm-cm resistivity material which results in a spreading resistance of about 12 ohms. It is seen that the total capacitance, including the case (0.08 $\mu\mu$f), is about 0.1 $\mu\mu$f for the negatively biased condition; the capacitance increases to a value nearly 15 times greater for a positive bias, which produces a forward current flow of a few microamperes. The resistive component of the impedance is still very high, however, and the capacitance may be increased to a value nearly 70 times the reverse bias value before appreciable forward current begins to flow.

Fig. 5 is a plot similar to that of Fig. 4, showing the resistive and capacitive variations with bias for a GaAs diode made with 0.003 ohm-cm material. This type of diode has a lower spreading resistance, and the best diodes have cutoff frequencies well in excess of 100 kMc. This type of GaAs diode has, in general, given us the best noise figures in most parametric amplifier applications. It will be noticed that the capacitance may be changed over a range of about three times (0.3 to 0.9 $\mu\mu$f) with the resistance remaining sufficiently high so that not more than plus or minus one or two microamperes of current will flow. A typical fixed bias to use when employing this type of diode in a parametric amplifier is about minus 1.2 volts. An available pump power of less than 10 milliwatts will normally be required to drive the diode over the range mentioned.

Fig. 6 shows the measured voltage-capacitance curve for a typical experimental GaAs point-contact diode formed at low current densities. (The barrier voltage, $\phi_0 = 0.5$, was obtained by plotting $1/C^2$ against the applied bias; ϕ_0 is the intercept on the voltage axis.) It is seen that the barrier capacitance of the diode proper (case capacitance of 0.08 $\mu\mu$f subtracted) follows very nearly the inverse square root of the voltage rule which one would expect for the case of an abrupt junction. If

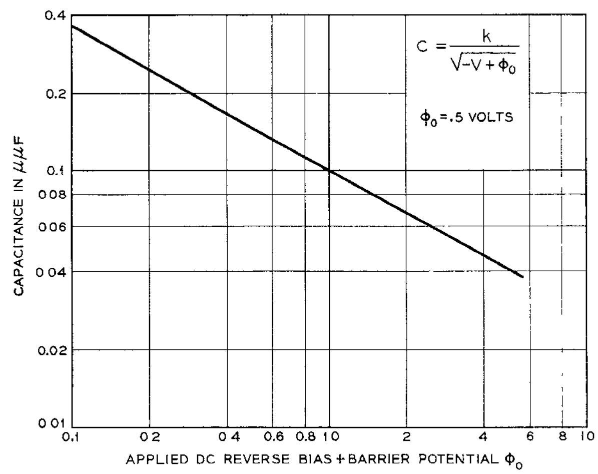
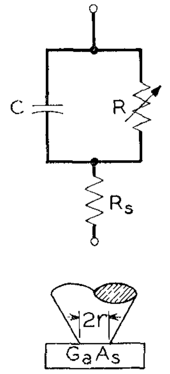


Fig. 6—Measured voltage-capacitance curve for a typical experimental GaAs point-contact diode formed at low current densities.

one forms the diodes at higher levels, a more graded junction will, in general, result and the capacity-vs-bias relation tends to approach a cube-root curve rather than the approximate square-root variation shown in Fig. 6.

There are a few rather simple formulas which may be used to tentatively evaluate the performance expected from varactor diodes used in parametric amplifier applications. These relations are shown in Fig. 7. The inductance of the diode is assumed to be small and has been neglected in the simplified analysis. The generally accepted simplified equivalent circuit of the diode is shown on the left of Fig. 7. When the diode is used as a variable reactance in a parametric amplifier, it is biased into a nonconducting region and the barrier resistance R becomes very high, of the order of megohms, and may be dropped from the active circuit. The



$$Q = \frac{X_c}{R_s} = \frac{1}{\omega C R_s}$$

$$f_c = \frac{1}{2\pi C R_s} \quad \text{WHEN } Q=1$$

$$R_s = \frac{\rho}{4r} = \frac{1}{4r N \cdot q \cdot b}$$

$$C = \frac{\pi r^2 (\epsilon \cdot q \cdot N)^{1/2}}{\sqrt{2}(\phi_0 - V)^{1/2}}$$

$$R_s C \propto r \left[\frac{\epsilon^{1/2}}{b \cdot N^{1/2}}\right]$$

$$\text{FIGURE OF MERIT} = f_c(\Delta_c) = \frac{\Delta_c}{2\pi C R_s}$$

Fig. 7—Approximate formulas for tentative evaluation of the expected performance of varactor diodes in parametric amplifiers.

resulting effective high-frequency circuit thus becomes the barrier capacity C in series with the base or spreading resistance R_s. The expression for the Q of the diode at high frequency is then simply the ratio of the resistive and reactive components, and the cutoff frequency f_c is taken as the frequency at which Q becomes equal to one. In parametric diodes, we wish the Q to be as high as possible for efficient operation at the highest possible frequency.

As may be seen from the equations, the cutoff frequency f_c is inversely proportional to the product of C and R_s, and a diode design which minimizes this product is very desirable. The equations further show the important factors which contribute to the value of C and R_s. Other symbols used in these equations are as follows:

r = radius of point contact in cm
N = carrier density in cm^{-3}
q = charge on electron (1.6×10^{-19} coulomb)
ρ = resistivity in ohm-cm
b = mobility, cm^2/volt-second
ϵ = dielectric constant ($\epsilon_0/36 \times 10^{-9}$)
ϕ_0 = barrier height in volts
V = bias voltage.

The equation showing the factors that are proportional to the R_sC product indicates why a small-area GaAs point-contact diode should be a superior performer compared to other diodes. The small point contact means that the radius r is very small and it is seen that r enters the equation directly. The dielectric constant of the material used is also important and should be made as low as possible. Silicon has a dielectric constant $\epsilon_0 = 12$, germanium is 16, and GaAs is only 11.

The mobility of ordinary P-type silicon as used in the commercially available 1N-series diodes will have values of the order of only a few hundred. N-type germanium used in microwave diodes will have mobilities in a higher range, possibly between one and two thousand. N-type gallium arsenide, doped to levels desired for microwave diodes, can be expected to have mobilities in a range as high as four or five thousand. It is seen in the equations that the value of R_s, which we wish to make small, is inversely proportional to the mobility and thus the higher we can make the mobility, the higher will be the cutoff frequency.

From the formula for R_sC product, it may also be seen that it is desirable to make the carrier density as high as possible. However, since the mobility and the resistivity of the semiconductor are also related to the carrier density, the R_sC product for a given diode will partly depend on the choice of other desired diode characteristics.

The final equation in Fig. 7 suggests a figure of merit for varactor diodes. This equation states that, in addition to the cutoff frequency, some factor related to the change in capacity with drive Δ_c should also be included. Further, a figure of merit, to be meaningful, must be accompanied by a statement regarding the bias voltage associated with the measured values presented. The matter of a completely satisfactory definition for a varactor figure of merit is not simple and for more complete information on some of the many factors involved, the reader is referred to a few recently published notes.[7,8]

Noise-Figure Measurements

Several measurements of the input-noise figures of parametric amplifiers using our GaAs point-contact diode have been made. Parametric amplifiers are unique in that, depending upon operating conditions, the noise figures resulting can be quite different; it is therefore necessary to state the conditions under which a given series of measurements are made in order for them to be meaningful. The noise-figure measurements presented in the following paragraphs were all made under so-called degenerate conditions, where the signal frequency to be amplified is very nearly one-half the frequency of the applied pump. Fig. 8 is a schematic drawing of a parametric amplifier operating in such a mode. As shown in the upper left of the figure, the signal is introduced at a frequency slightly below half the frequency of the pump. This signal flows to the circulator input port 1 and travels to port 2 where it passes to the right through a pump-rejection filter into the parametric-diode circuitry. The diode is pictured as a lumped parallel circuit having resistance, inductance and a capacitance which will vary at the frequency of the applied pump. An amplified signal s and its image p-s will be generated and pass outward to the left toward the circulator going into port 2 and emerging from port 3, appearing frequency-wise as shown in the lower left of the figure. When a noise-figure measurement is

[7] R. C. Knechtli and R. D. Weglein, "Diode capacitors for parametric amplification," *J. Appl. Phys.*, vol. 31, p. 1134; June, 1960.
[8] K. E. Mortenson, "Comments on diode capacitors for parametric amplification," *J. Appl. Phys.*, vol. 31, p. 1135; June, 1960.

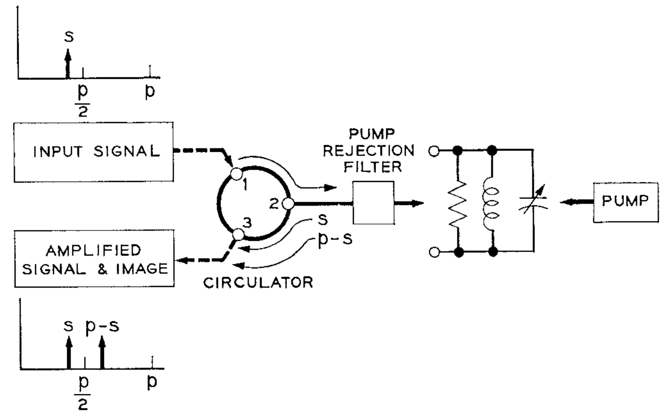


Fig. 8—Schematic drawing of a parametric amplifier operating in the degenerate mode (courtesy E. D. Reed).

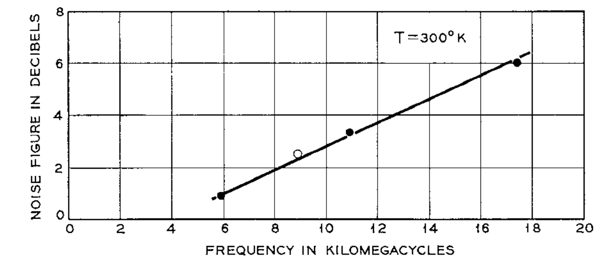


Fig. 9—Room temperature, degenerate mode, GaAs parametric amplifier noise-figure measurements.

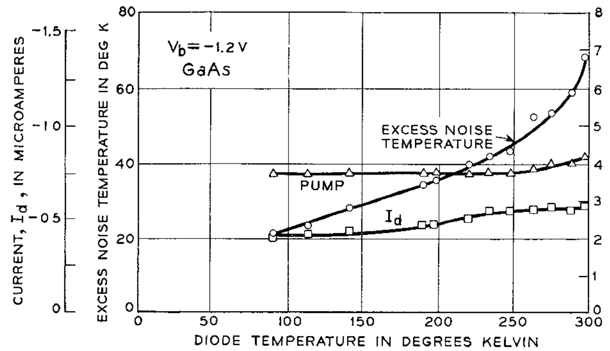


Fig. 10—Measured excess noise temperature, pump power and diode current for a typical GaAs point-contact diode cooled from 300°K down to 90°K.

made with a broad-band source, equal amounts of noise power are introduced at both the signal and image frequencies. The double-sideband noise figures thus measured for the degenerate case are 3 db better than for the single-sideband operation. When the amplifier is used for radio astronomy star-noise measurements or in connection with a receiving system employing synchronous detection in association with a synchronized transmitter, the double-sideband degenerate noise figures apply. All of the noise figures shown in Figs. 9 and 10 were measured under double-sideband degenerate conditions.

The degenerate room-temperature noise-figure measurements given in Fig. 9 were made by several different people and represent typical figures that have been obtained. The 6-kMc point was measured by Venohara; the 9-kMc point was supplied by W. L. Whirry, Hughes Aircraft Company, Culver City, Calif.; the 11-kMc point was supplied by DeLoach.[4] DeLoach also made the measurements represented by the point at 17.4 kMc[5] and he further reports that oscillations and amplification have been obtained in a parametric amplifier of his design, operating at a signal frequency of 30 kMc and pumped with a 60-kMc oscillator.[5] In the latter case, the GaAs diode details were removed from their cartridge holder and mounted directly across the high-frequency waveguide. In practically all cases, better noise figures than those shown in Fig. 9 have subsequently been obtained either by the use of improved circuitry or specially selected diodes. A quantity of these diodes have recently been fabricated by N. C. Vanderwal, Bell Telephone Laboratories, Allentown, Pa., for circuit evaluation.

Fig. 10 gives the results of further experiments conducted by Uenohara,[3] which give the measured excess noise temperature, pump power and diode current for a typical GaAs point-contact diode cooled by liquid nitrogen from room temperature, 300°K, down to 90°K. The excess noise temperature shown in Fig. 10 may be translated to noise figures in db, if desired, by use of the approximate rule that, in this range, 7 degrees excess noise temperature is equivalent to 1/10 db noise figure. The gain of the amplifier was held constant at 16 db.

It is interesting to note that the excess noise temperature decreased almost linearly with the diode temperature from 220°K down to 90°K. By extending the curve to the left, one can estimate that the noise contribution from the circuit only was about 10°K in this case. Uenohara has measured selected GaAs point contact diodes that are even better than the case plotted in Fig. 10. One diode, cooled to the temperature of liquid nitrogen, showed an excess noise temperature of only 12°K at 6 kMc.

Conclusion

It is interesting to note that the excess noise temperature in a system using a cooled GaAs parametric amplifier is approaching that obtainable with our present-day masers operating at the same frequency. Because of its simplicity, such a parametric amplifier may become a reasonable competitor of the maser, especially when one considers the relatively large noise contributions from other portions of typical operating systems.