Correspondence

An X-Band Parametric Amplifier with Closed-Cycle Cooling

The objective in this work has been to utilize proved parametric amplifier techniques along with a relatively low cost reciprocating cryogenic cooler to achieve very low-noise parametric amplification in the X-band frequency region.

Operation of parametric amplifiers and other devices at reduced temperature to achieve improved noise performance is certainly not new. Many investigators, including Uenohara [1], Carl Blake of M.I.T. [2], and Rucker, et al., [3] have operated amplifiers at 77° or 4.3°K by use of liquid nitrogen or helium. These systems have the basic disadvantage in that the liquid coolant boils away and must be replenished relatively often.

It becomes apparent then that a closed cycle system which does not require replenishment of the coolant is highly desirable.

System Elements

The amplifier-system elements developed for this work, shown in Fig. 1, consist of a four-port switchable circulator which is not cooled, the parametric amplifier, a vacuum-tight container, and a suitable cooler—in this case a Norelco "Cryogem." The circulator-amplifier combination is shown enlarged in Fig. 2, with half of the amplifier body removed to expose its internal construction. The amplifier consists of an input transformer; a low-pass filter which prevents pump leakage from the amplifier and limits the idle circuit to the region surrounding the diode; and a short section of reduced height waveguide, which serves as a pump-power input port and adjusts the diode to resonance at the idle frequency. The body is constructed of tellurium copper because of its excellent machineability and good thermal and electrical conductivity at low temperatures.

The amplifier uses commercially available gallium arsenide diodes having spreading resistance R_s of approximately 2.0 ohms, and dynamic quality factor γQ of about 7.5 at room temperature. Best performance to date has been achieved with a Sylvania 5047C pill-type varactor. The generator impedance was adjusted to approximately 15.0 ohms for optimum noise performance consistent with high gain in the manner prescribed by Blackwell and Kotzebue [4]. A pump frequency of 23.8 Gc/s was chosen. This choice is below the optimum predicted by Blackwell and Kotzebue for optimum noise performance. Several factors influenced this choice. First, at reduced temperatures, the choice of the optimum pump frequency becomes less important; second, excessive power dissipation and resultant diode junction heating at too high pump frequencies have been observed; finally, proved klystrons operating at 23.8 Gc/s with adequate power are readily available.

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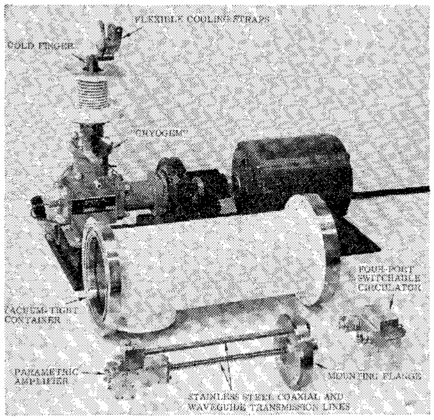


Fig. 1. Amplifier system elements.

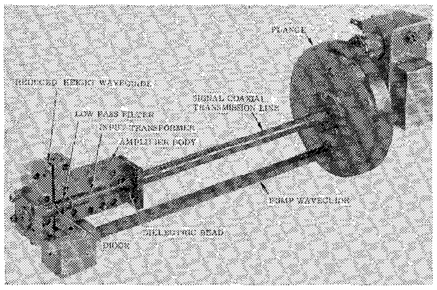


Fig. 2. Enlarged view of circulator-amplifier combination.

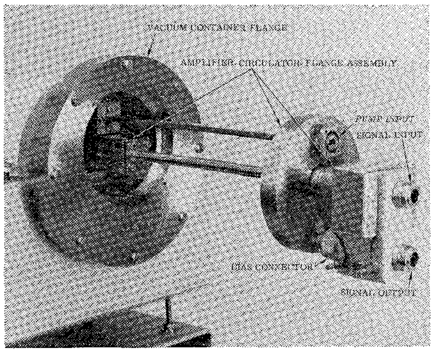


Fig. 3. Amplifier-circulator assembly partially inserted in vacuum-tight container.

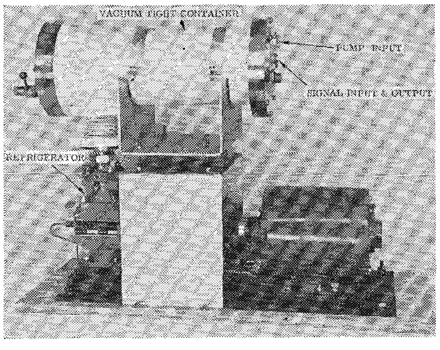


Fig. 4. Photograph of system excluding input circulator.

A section of thin-walled stainless steel coaxial line connects the amplifier to the four-port circulator. To provide thermal isolation between the cooled amplifier body and the uncooled circulator, this transmission line must be relatively long. Pump power is connected to the amplifier in a similar fashion by a thin-walled stainless steel waveguide. For cooling, this assembly (which includes a mounting flange and vacuum seals) is inserted into the vacuum-tight container. Figure 3 shows the assembly partially inserted. The amplifier is attached to the cold "finger" of the cooler by means of flexible copper straps. Next, the container is evacuated to further reduce the heat leaks into the amplifier body. A vacuum approaching 10^{-6} millimeters of mercury is obtained; no leaks have been detected by helium mass spectrometry measurements. The system has been operated for periods exceeding 24 hours without continuous pumping. Outgassing of the materials used to build portions of the amplifier and container may necessitate continuous vacuum pumping of the container for extended operation. Should continuous pumping be required, an ionic high vacuum pump can be used. The entire amplifier assembly, excluding the switchable circulator, is shown in Fig. 4.

Since the refrigerator unit is of the reciprocating piston type, consideration was given to mechanical vibration. To minimize possible problems, a bellows assembly was used at the joint between the cooler and the container, and a "spider" type mount was employed to hold the amplifier rigidly in place. The spider mount consists simply of three 0.010-inch diameter stainless steel wires which connect to the amplifier at 120° intervals and anchor to the container body. Pins similar to those used to adjust the tension of a guitar string are used to tighten the wires.

Performance

The amplifier body reaches a stable temperature of approximately 40°K two hours after the cooler is started, indicating that the cooler is operating under approximately 4 watts of load. Figure 5 is a graph supplied by the Cryogen manufacturer, and shows watts of load as a function of the achievable temperature in degrees. Our load of 4 watts was determined from this graph. Temperature was measured by attaching a special thermistor, designed for low-temperature measurements, to the amplifier body. (The thermistor is manufactured by Keystone Carbon Company of St. Marys, Pa.) This termistor was first calibrated at room temperature and at 77°K. Further calibration points at 63.3°, 53.9°, and 46.9° were then obtained by reducing the pressure on a container of liquid nitrogen to 100, 10, and 1.0 millimeters of mercury, respectively. Figure 6 shows thermistor temperature as a function of resistance. The large resistance changes which occur in the temperature range of 40 to 77°K make it possible to determine temperature by a simple resistance measurement.

Under room temperature conditions, typical effective noise temperatures of 265°K were obtained for the assembly over a tuning range of 6.8 to 7.8 Gc/s. The amplifier alone exhibits typical effective noise temperature of 195°K at room temperature. A summary of room temperature performance follows:

Tuning range	6.8 to 7.8 Gc/s (pump-tuned)
Gain	0 to 20 dB
Bandwidth	15 Mc/s nominal
System effective noise temperature	265°K (typical)
Amplifier effective noise temperature	195°K (typical)

When the amplifier is cooled to approximately 40°K, the tuning range shifts to a range of 7.0 to 8.0 Gc/s. This shift results from mechanical changes in the amplifier body and a change in the average capacitance of the diode. After the amplifier has finished cooling, retuning is accomplished by resetting pump frequency. Nominal bandwidth of the amplifier system is unchanged by cooling. Figure 7 shows the effective noise temperature achieved as a function of signal frequency when the amplifier is cooled to 40°K. As indicated, the nominal effective noise temperature is 80°K for the system (including all input losses), and 45°K for the one-port amplifier alone. The amplifier noise temperature is approximately 20° higher than the theoretical temperature of about 25°K. In other words, the improvement is about 83 per cent of the theoretical.

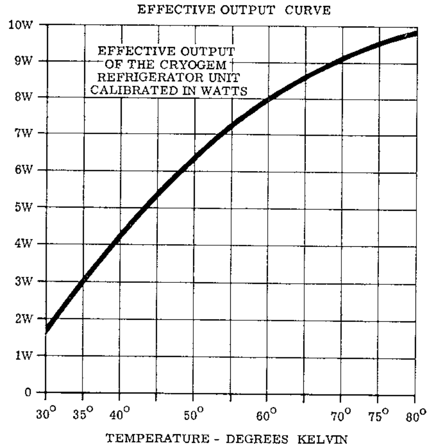


Fig. 5. Thermal load vs. temperature.

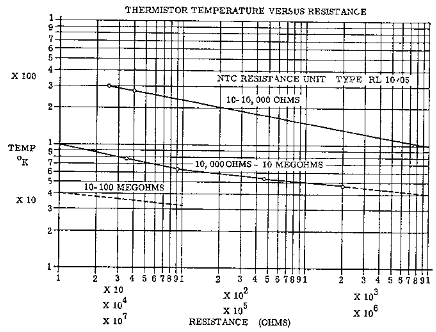


Fig. 6. Thermistor temperature as a function of resistance.

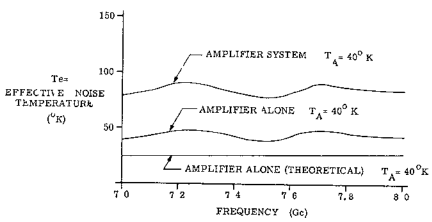
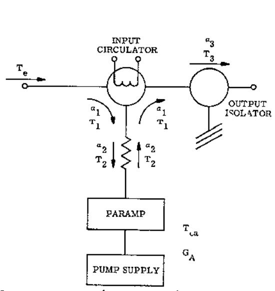


Fig. 7. System and amplifier noise temperature when amplifier is operated at 40°K.



$$T_e = \frac{1-\alpha_1}{\alpha_1} T_1 + \frac{1-\alpha_2}{\alpha_1 \alpha_2} T_2 + \frac{1}{\alpha_1 \alpha_2} T_{ea} + \frac{1-\alpha_2}{\alpha_1 \alpha_2^2 G_A} T_2 + \frac{1-\alpha_1}{\alpha_1^2 \alpha_2^2 G_A} T_1 + \frac{1-\alpha_3}{\alpha_1^2 \alpha_2^2 \alpha_3 G_A} T_3 \quad (1)$$

α_1 = TRANSMISSION COEFFICIENT OF CIRCULATOR
α_2 = TRANSMISSION COEFFICIENT OF COAXIAL TRANSMISSION LINE
α_3 = TRANSMISSION COEFFICIENT OF OUTPUT CIRCULATOR - TYPE ISOLATOR
T_1 = CIRCULATOR TEMPERATURE (°K)
T_2 = AVERAGE TEMPERATURE (°K) OF COAXIAL TRANSMISSION LINE
T_3 = CIRCULATOR - TYPE ISOLATOR TEMPERATURE (°K)
T_{ea} = NOISE TEMPERATURE (°K) OF PARAMETRIC AMPLIFIER STRUCTURE
G_A = GAIN OF PARAMETRIC AMPLIFIER

Fig. 8. Schematic diagram of system.

Discussion and Calculations

Some interesting extrapolations of these results can be made if the effective noise contribution of each system element is considered. The system is shown schematically in Fig. 8. The effective noise temperature is given by (1) where the α's are the transmission coefficients of each lossy element, the T's are the physical temperatures of these elements, and T_{ea} is the noise temperature in °K of the amplifier at its input.

The components used in our amplifier system exhibit the following typical characteristics:

$$\alpha_1 = 0.945(-0.25 \text{ dB}) \qquad T_1 = 290°K$$
$$\alpha_2 = 0.921(-0.3 \text{ dB}) \qquad \overline{T}_2 = 165°K \quad (1)$$
$$\alpha_3 = 0.945(-0.25 \text{ dB}) \qquad T_3 = 290°K$$

Under these conditions, the effective noise contributions (references to the input) which result from each circuit element are:

	°K
1) Input circulator (first pass)	16.89
2) Coaxial transmission line (first pass)	14.99
3) Amplifier	51.80
4) Coaxial transmission line (second pass)	1.21
5) Input circulator (second pass)	0.16
6) Output circulator-type isolator	0.17
	T_e = 85.22°K

The first two terms are significant contributions to the system-input excess noise temperature. These contributions and other less significant ones can be reduced appreciably by reducing the temperature of the input circulator. Typically, if the circulator temperature is reduced to 77°K, a system effective noise temperature of about 60°K should be obtained. If one assumes that further cooling of the amplifier will result in similar reductions in effective noise temperature, another useful extrapolation which is evident is the effective noise temperature one would expect to achieve by reducing the circulator temperature, and by reducing the amplifier temperature further as well. Sophisticated multiple-heat station coolers are now available which allow amplifier operation near 4.3°K and circulator operation near 77°K. If the amplifier and circulator were operated at these temperatures, a system effective noise temperature of about 13°K should be obtained. This corresponds to an amplifier noise temperature near 6°K.

Each of these changes is probably within the state of the art at present. Circulators capable of operation at 77°K have been constructed, dependable coolers for lowering the amplifier temperature to about 5°K now have become available, and amplifiers capable of operating at this temperature have been demonstrated.

Conclusions

Several conclusions can be drawn from these measurements and calculations. First, an uncomplicated, closed-cycle cooled amplifier has been built and performs acceptably, yielding 83 per cent of the theoretical improvement in the system effective noise temperature. Second, logical extrapolations of the results obtained indicate that much lower system noise temperatures of about 15°K should be achievable in the 7.0 to 8.0 Gc/s frequency range by use of techniques and devices already in existence or achievable without undue effort.

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References

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Band-Pass Filters with Steep Skirt Selectivity

Band-pass filters exhibiting low pass-band insertion loss and extremely steep rejection skirts can be realized by means of

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