MILLIMETER ARRAY
MEMO NO. 67

HFET'S AND RECEIVERS FOR THE MILLIMETER-WAVE ARRAY

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1. Introduction

There has been considerable progress in the performance of HFET's (or as they are known by other names: MODFET's, HEMT's, TEGFET's) at millimeter wavelengths in the past several years. This memorandum attempts to assess the possible impact of these developments on the design of receivers for the Millimeter-Wave Array and to identify important research issues pertaining to HFET's which should be answered before the electronics design phase begins.

2. HFET Amplifiers

A summary of the typical performance of NRAO cryogenic HFET amplifiers is presented in Figure 1. The noise temperature data are referred to the cold input of the amplifiers [1], [2]. The noise performance of these amplifiers is plotted with the minimum noise measure of the FHR02X HEMT, a quarter-micron gate device available from Fujitsu. Also, the noise temperature of the 38-45 GHz amplifier is plotted with the minimum noise measure of the .1 μm gate PHEMT device from ROHM Research [3], [4]. The data for the 4 K masers [5]-[7] are given for comparison. The amplifier examples demonstrate that for a bandwidth of around an octave or less the amplifier average noise temperature is equal to the minimum noise measure at the highest frequency within the band.

An excellent agreement between predicted and measured noise performance of the amplifiers [1], both at room and cryogenic temperatures, was a result of the development of a FET noise model [8]-[10]. This model allows also for a reasonable prediction of future performance. A minimum noise measure vs. frequency of a "futuristic" HFET is presented in Figure 2 for different ambient temperatures. A model of this device was created by assigning to the equivalent circuit of a current experimental HFET [11] the values of equivalent gate and drain temperatures (which determine the noise properties of a device) measured on the best devices currently being used in the construction of amplifiers at NRAO.

The "futuristic" device under consideration was the .15 μm long gate HFET using AlInGa/GaInAs on an InP wafer structure from GE [11]. The published room temperature noise measure data of GE devices [11] fit extremely well the model prediction, as do the data from Hughes and TRW on similar devices [12], [13]. The data for this device at other ambient temperatures were obtained under the assumption that the equivalent gate and drain temperatures behave like those for .15 μm ROHM Research HFET routinely used in our laboratory. Therefore, the term "futuristic" used for this device reflects only an uncertainty about its cryogenic performance.

3. HFET's as Sources of Millimeter-Wave Power

The output power of state-of-the-art HFET's for frequencies up to 100 GHz is now comparable with that of Impatt diodes and better than Gunn diodes [14]. Recent HFET results are summarized in Figure 3 [14] (an extensive comparison with other sources is given in [15]). Current millimeter-wave systems are using phase-locked Gunn oscillators and whisker-contacted Schottky-diode frequency multipliers as the sources of local oscillator power. Both Gunn oscillator and multipliers require mechanical tuning. A notable exception is the design of LO chain for the FCRAO 15-element array [16] in which a phase-locked YIG is followed by a wideband FET power amplifier and a cryogenic, fixed-tuned multiplier to deliver more than 4 mW of over 88 to 115 GHz range [16]. Not much information is available on fundamental FET oscillators in W-band and above, although FET oscillators or oscillator-(multiplier)-power amplifier chains are replacing diode oscillators (Gunn, Impatt) in most applications at lower microwave frequencies. Also, no information is available on cryogenic properties, either on FET fundamental oscillators or power amplifiers, but it is expected that their performance should greatly improve upon cooling.

4. Impact of Advances in HFET Technology on the Design of Receivers for the Millimeter-Wave Array

A reasonable attempt to predict the future in a rapidly developing field of technology should be based on:

- an assessment of the rate of development of a given field which, in most cases, is determined by the interest it generates from the point of view of military and commercial applications;
- an understanding of the limitations of current technology.

Both low-noise HFET's and power HFET's are in the focus of many research programs and their development will continue to be strongly driven by military and commercial markets. An understanding of their noise, small signal and large signal characteristics and underlying technology limitations is now emerging. Computer-aided design tools, both commercial and in-house, are now available.

The consequences of this progress on the development of receivers for the MMA cannot be overestimated. It is interesting to recall that the first paper on cryogenic properties of HFET's was published in 1985 [17]. It reported on X-band measurements of a couple of experimental HFET's developed at Cornell University. Today all receivers for the VLBA employ HFET's amplifiers. The performance of these receivers and also of SIS/HFET IF [20] receivers is compared in Figure 4 (courtesy of A. R. Kerr) with the predicted performance of receivers employing <u>current</u> experimental devices (compare Figure 2). It becomes rather obvious that HFET receivers would be the preferred solution, not only in the 9-mm window atmospheric window but also in the 3-mm window. (The MMA proposal suggests the use of SIS receivers in the 3-mm window [18].)

A successful demonstration of the model-predicted performance at cryogenic temperatures of a current experimental HFET could have a tremendous impact not only on the design of the 68-115 GHz receivers, but also on receivers for other frequency bands: 130-183 GHz, 195-314 GHz and 330-366 GHz. It stems from the observation that the device capable of exhibiting ~ 50 K noise measure at 100 GHz could be used to build 10-20 GHz IF amplifiers with an average noise of 6 K. Even larger bandwidths are possible, for instance, 20-40 GHz with average noise of 20 K or so. This could facilitate the use of SIS junctions as wideband frequency converters with considerably relaxed requirements for LO tuning. Not only would it allow the instantaneous access to a large bandwidth for radio astronomy observations, but also it would greatly simplify the separation of sidebands. Both of these issues are now perceived as challenging design and engineering problems in the current MMA design concept [19].

Finally, HFET's could provide sufficient local oscillator power at frequencies in excess of 100 GHz, and probably under cryogenic cooling up to 200 GHz. Also, a combination of HFET amplifiers and varactor (or HFET) multipliers (possibly also cryogenically-cooled) for local oscillator applications throughout millimeter-wave range is ultimately to be extremely competitive with current solutions.

5. Conclusion

There are several areas in which a concentrated NRAO effort should be strongly encouraged:

- evaluation, testing and establishment of small signal and noise models of currently available experimental HFET's at room and cryogenic temperatures (an effort similar in scope to that established during the development of receivers for the Voyager/Neptune encounter),
- evaluation, testing and establishment of nonlinear device models (also for cryogenic temperatures) for power HFET's at millimeter wavelengths,
- a study of SIS junctions as frequency converters with high IF frequency (the properties may differ from those of current low-IF mixers due to the fact that IF frequency energy quanta are no longer negligible compared with the band-gap energy; also the impedances at both sidebands would be drastically different [19]), and
- a study of the interaction between an SIS mixer and its IF amplifier with high IF and wide bandwidth (*e.g.*, 10-20 GHz or 20-40 GHz). This interaction can profoundly affect the overall noise performance of the receiver [19].

HFET technology, both in low-noise and power applications, is the most dynamically developing field among those likely to influence the design of the MMA. Answers to the questions posed in the preceding could influence the design of SIS mixers (wideband IF vs. narrow-band IF), local oscillators (HFET power amplifiers and HFET oscillators vs. Gunn diode oscillators), cryogenic systems (4 K vs. 12 K coolers), optics (sideband separation), multiple-frequency operation, and signal transmission (IF bandwidth). In essence, HFET and related development may not be viewed as possibly leading to a replacement of one building block with another, but as having a profound effect on the whole MMA receiver design.

6. References

[1] M. W. Pospieszalski, J. D. Gallego, and W. J. Lakatosh, "Broadband, Low-Noise, Cryogenically-Coolable Amplifiers in 1 to 40 GHz Range," in *Proc. 1990 MTT-S Int. Microwave Symp.*, pp. 1253-1256, Dallas, TX, May 1990.

[2] M. W. Pospieszalski, "Cryogenically-Cooled, HEMT Amplifiers and Receivers in 1-50 GHz Range: State-of-the-Art," *IAU Colloquium No. 131: Radio Interferometry - Theory, Techniques and Applications*, Socorro, NM, October 1990.

[3] R. E. Lee, *et al.*, "Ultra-Low-Noise Millimeter-Wave Pseudomorphic HEMT's," *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-37, pp. 2086-2092, Dec. 1989.

[4] S. Weinreb, *et al.*, "Millimeter-Wave Noise Parameters of High Performance HEMT's at 800 K and 17 K," in *Proc. 1989 IEEE Int. Microwave Symp.*, pp. 813-816, Long Beach, CA, June 1989.

[5] S. M. Petty and D. L. Trowbridge, "Low-Noise Amplifiers," in *Deep Space Network - Radio Communications Instrument for Deep Space Exploration*, JPL Publication 82-104, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, July 1983.

[6] J. Shell and D. Neff, "A 32 GHz Reflected-Wave Maser Amplifier with Wide Instantaneous Bandwidth," in *Proc. 1988 IEEE MTT-S Int. Microwave Symp.*, pp. 789-792, New York, NY, June 1988.

[7] J. Shell, private information, 1991.

[8] M. W. Pospieszalski, "A New Approach to Modeling of Noise Parameters of FET's and MODFET's and Their Frequency and Temperature Dependence," National Radio Astronomy Observatory Electronics Division Internal Report No. 279, Charlottesville, VA, July 1988.

[9] M. W. Pospieszalski, "Modeling of Noise Parameters of MESFET's and MODFET's and Their Frequency and Temperature Dependence," *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-37, pp. 1340-1350, Sept. 1989.

[10] M. W. Pospieszalski and A. C. Niedzwiecki, "FET Noise Model and On-Wafer Measurement of Noise Parameters," in *Proc. 1991 IEEE MTT-S Int. Microwave Symp.*, pp. 1117-1120, Boston, MA, June 1991.

[11] K. H. Duh, *et al.*, "W-Band InGaAs HEMT Low-Noise Amplifiers," in *Proc. 1990 Int. Microwave Symp.*, pp. 595-598, Dallas, TX, May 1990.

[12] S. E. Rosenbaum, *et al.*, "AlInAs/GaInAs on InP HEMT Low-Noise MMIC Amplifiers," in *Proc. 1991 Int. Microwave Symp.*, pp. 815-819, Boston, MA, June 1991.

[13] P. D. Chow, *et al.*, "Ultra Low-Noise High Gain W-Band InP-Based HEMT Downconverter," in *Proc. 1991 Int. Microwave Symp.*, pp. 1041-1044, Boston, MA, June 1991.

[14] P. M. Smith, *et al.*, "Microwave and Millimeter-Wave Power Amplification Using Pseudomorphic HEMT's," *Microwave Journal*, vol. 33, p. 71, May 1990.

[15] R. Bradley, Ph.D. thesis, to be published.

[16] N. R. Erickson, *et al.*, "15-Element Imaging Array for 100 GHz," in Proc. 1990 Int. Microwave Symp., pp. 973-977, Dallas, TX, May 1990.

[17] S. Weinreb and M. W. Pospieszalski, "X-Band Noise Parameters of HEMT Devices at 300 K and 12.5 K," in *Proc. 1985 IEEE/MTT-S Int. Microwave Symp.*, pp.539-542, St. Louis, MO, May 1985.

[18] "The Millimeter Array," NRAO proposal to the National Science Foundation, July 1990.

[19] A. R. Kerr, private communication.

[20] A. R. Kerr and S.-K. Pan, "Some Recent Developments in the Design of SIS Mixers," *Int. J. Infrared & Millimeter Waves*, vol. 11, no. 10, pp. 1169-1187, Oct. 1990.

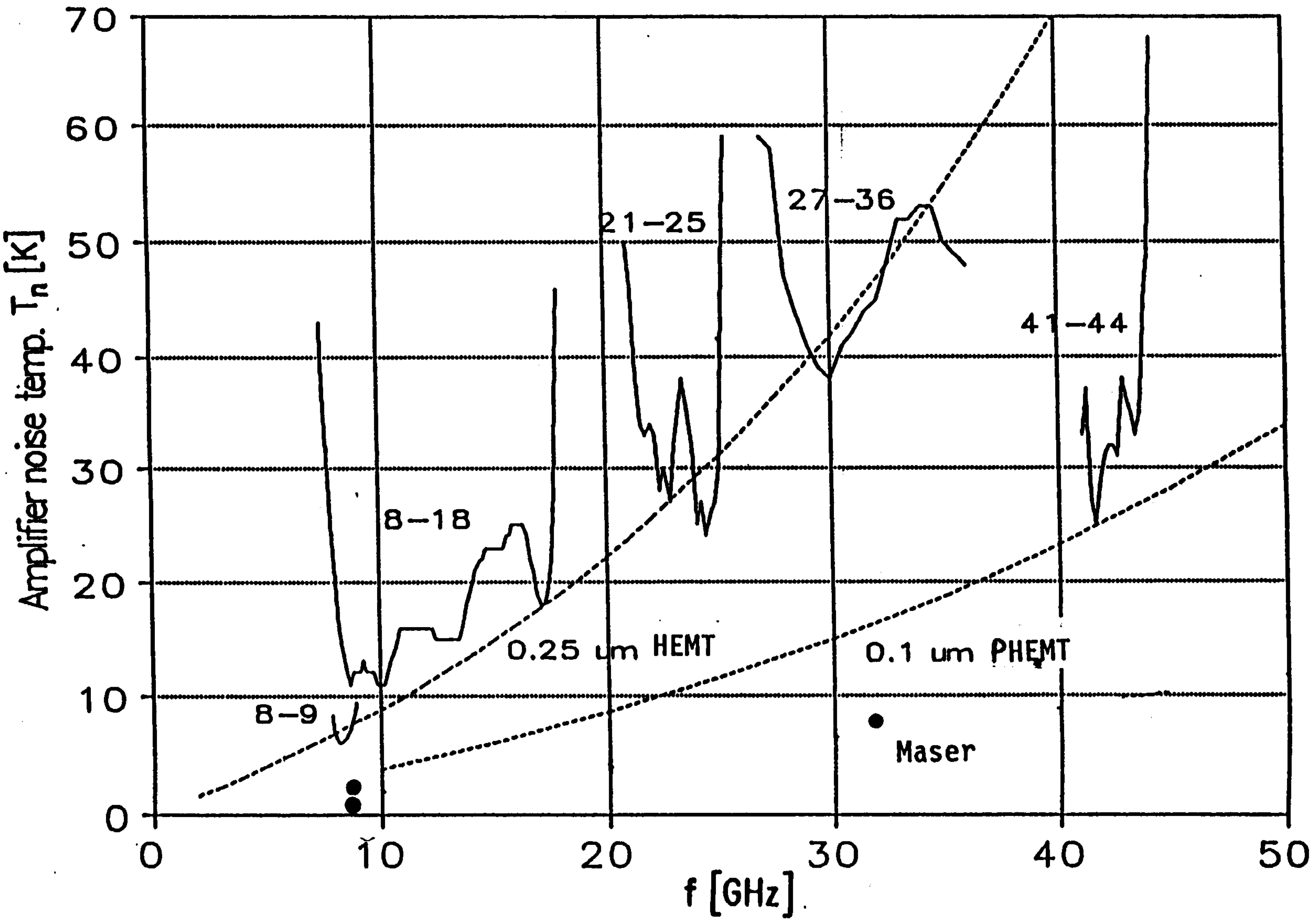

Fig. 1. Noise temperature of different amplifiers and minimum noise measure of FHR02X (.25 μm gate length) and H-CF-100-6 (.1 μm gate length) at $T_a = 12.5$ K. The noise performance of masers at 4 K and 1.9 K (a lower point at 8.4 GHz) is also shown for comparison.

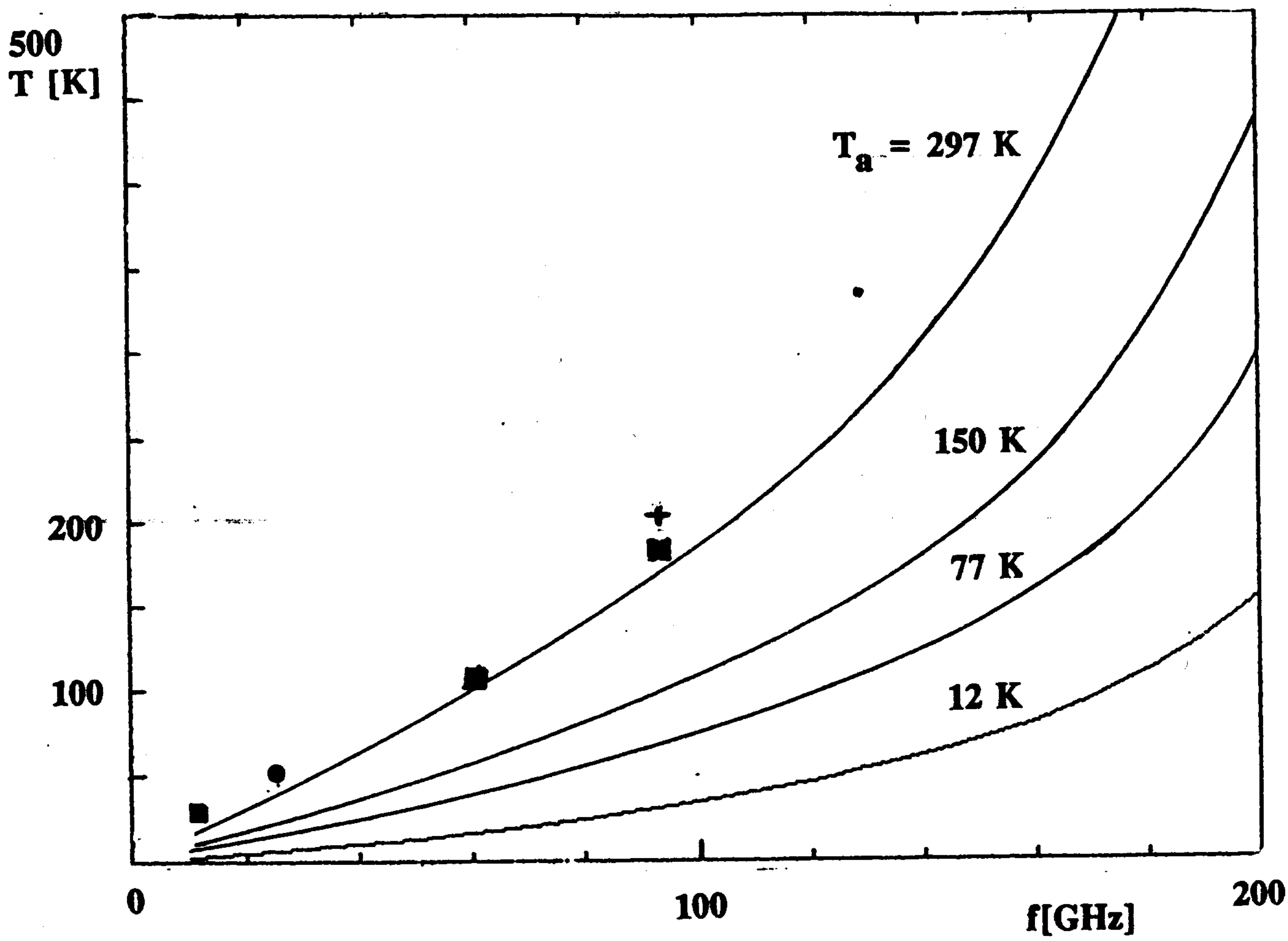

Fig. 2. A minimum noise measure of a "futuristic" HFET. Experimental results at room temperature for AlInAs/GaInAs on InP HFET's from three different laboratories are also shown: "■" GE [11], "•" Hughes [12], "+" TRW [13].

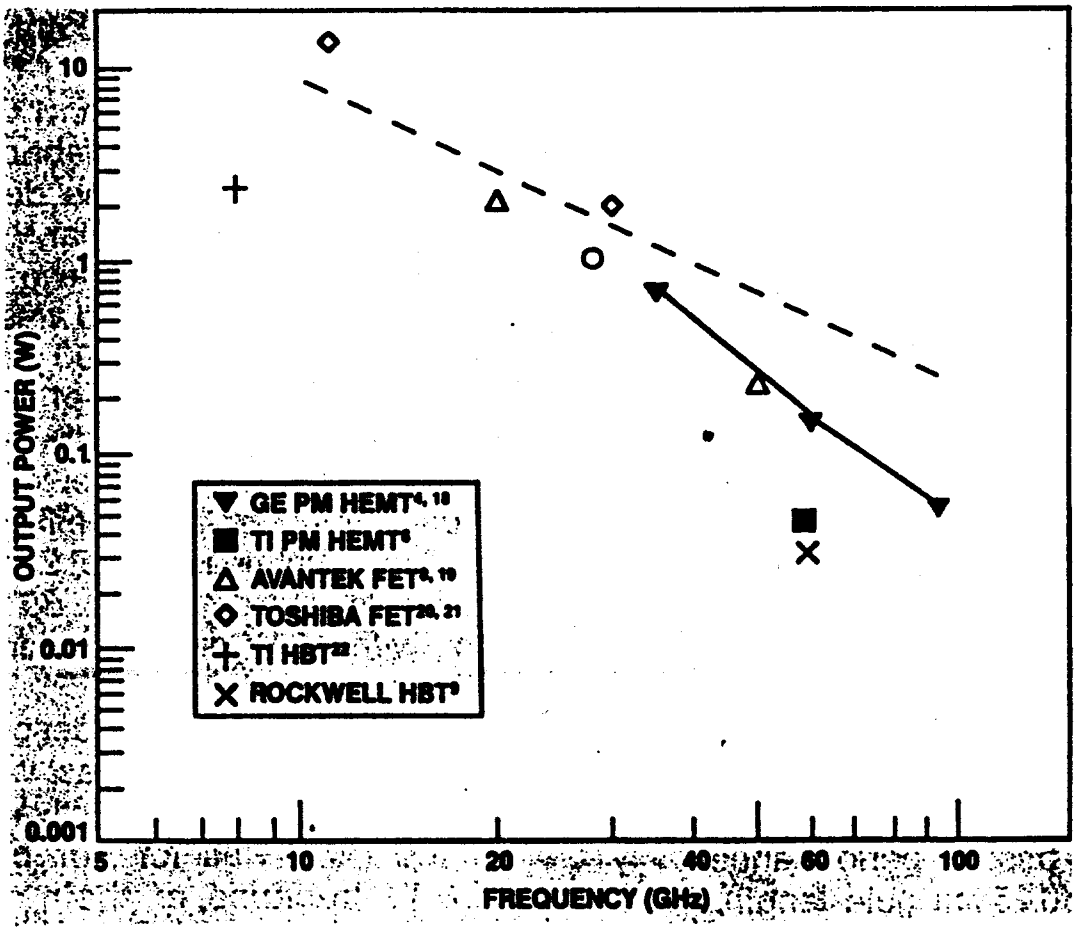

Fig. 3. A summary of the power performance of microwave and millimeter-wave transistors [14].

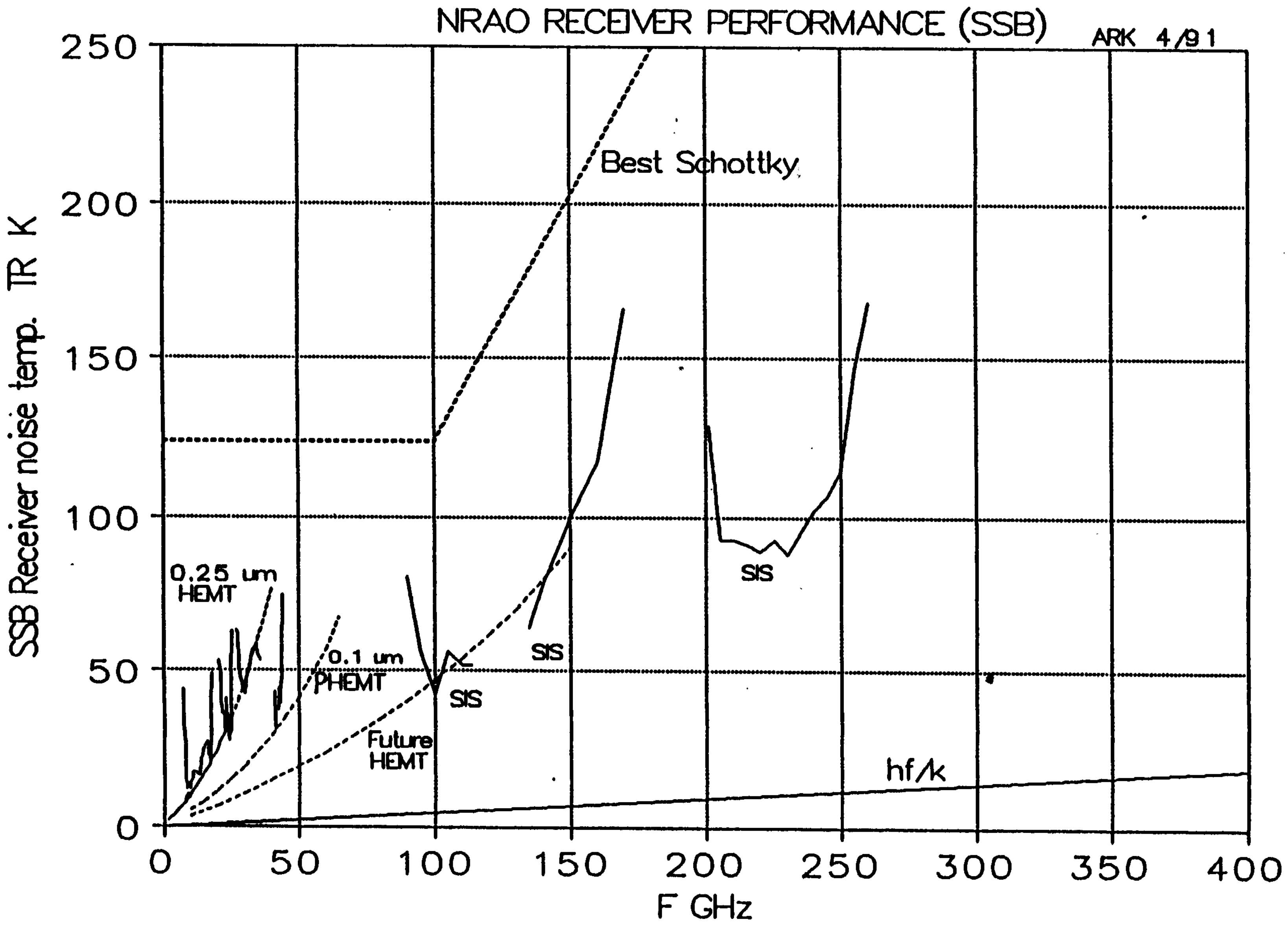

Fig. 4. A comparison of NRAO receiver performance with that expected from the current experimental devices ("future HEMT's").