1-22-96

A TOTAL POWER RADIOMETER WITH CONTINUOUS CALIBRATION IN FREQUENCY DOMAIN

M. W. Pospieszalski
National Radio Astronomy Observatory
Charlottesville, VA 22903

January 22, 1996

I. Introduction

The sensitivity of a total power radiometer is given by [1]:

$$\Delta T = T_s \sqrt{\frac{1}{B\tau} + \left(\frac{\Delta G}{G}\right)^2} \tag{1}$$

where B is the effective RF bandwidth, τ is the integration time, ΔG is the effective value of receiver power gain variations, G is the average predetection power gain and T_s is the system noise temperature.

Obviously, for the sufficiently large bandwidth B, the radiometer sensitivity may be limited by the predetection gain variation ΔG for a given integration time τ. A common way to avoid this limitation is to switch between the source of interest and a calibration source at time scales much smaller than those characteristic of gain changes. This type of receiver is known as the Dicke receiver [2], [3]. The sensitivity of a Dicke receiver is given by [2], [3]:

$$\Delta T = 2T_s \sqrt{\frac{1}{B\tau}} \tag{2}$$

where all the symbols have their previous meaning.

Another way of avoiding the limitation of sensitivity of the radiometer due to predetection gain variation is with a correlation receiver [1], [4], [5]. The sensitivity of a correlation receiver is given by:

$$\Delta T = \sqrt{2}\, T_s \sqrt{\frac{1}{B\tau}} \tag{3}$$

The performance of a Dicke receiver and its variations (for example, Graham's receiver) are quite often limited by the properties of the switch, which could be mechanical (including quasi-optical), ferrite or electronic. A recent study [6] shows that for wideband state-of-the-art amplifiers in K_a- through W-bands, Dicke's switching at a rate greater than several hundred Hz would have to be employed to achieve sensitivity given by (2). The performance of the correlation receiver and its variations (for example, phase-switching receiver) are limited by the presence of the signal which is common to both channels but not attributable to the source. Also, the way a multiplier is implemented could put significant requirements on the channel symmetry.

II. A Total Power Radiometer with Continuous Calibration in Frequency Domain

A schematic diagram of a total power radiometer with continuous calibration in frequency domain is shown in Figure 1. The principle of operation is based on the fact that gain variation in two different frequency bands of the same amplifier are perfectly correlated. This fact has been experimentally observed by Jarosik *et al.* [7]. In the schematic presented in Figure 1, the signal is observed in band defined by the bandwidth B_{RAD} of the filter while the reference signal from the black body standard is observed in the adjacent bandwidth B_{CAL}. There are several comments which should be made concerning the properties of the different components of this system.

The radiometer, preferably, should have about the same noise powers entering square-law detectors, both in signal channel and reference channel. Consequently, in the simplest case, bandwidth B_{RAD} and B_{CAL} should be equal, the gain of the amplifier in both channels should be equal and the system noise defined at the common post of a combiner (diplexer) should be equal. Under these conditions, the sensitivity of the radiometer of Figure 1 is given by

$$\Delta T = \sqrt{2}\ T_s \sqrt{\frac{1}{B_{RAD}\tau}} \tag{4}$$

which is exactly the same as for a correlation radiometer (3) or for a Dicke switched radiometer (2) with twice the bandwidth.

The frequency response of the filters, B_{RAD} and B_{CAL}, should not overlap. Actually, the noise power generated anywhere in the signal channel entering the reference channel detector diode and vice versa could be a factor further limiting the radiometer sensitivity. The design of the combiner could be in many forms, depending on a particular application and ease of realization, and will involve a combination of filters, Y-junctions and/or couplers and/or hybrids.

Although in principle the sensitivity of the proposed radiometer is not better than that of Dicke or correlation radiometers, in practice it should be due to several considerations.

A comparable Dicke radiometer should involve the radiometer of the total bandwidth $B_{RAD} + B_{CAL}$, that is, it will look at the source in twice the bandwidth, half of the time, as compared to the radiometer of Figure 1. But it would require very fast switching which, for the bandwidth of several GHz or more, would have to be done at a rate greater than 100 Hz [6]. This rate would usually require a switch which is lossy (electronic or ferrite) or unreliable, cumbersome and/or not repeatable (mechanical).

Recently, the author demonstrated very wideband, low-noise amplifiers [8], [9] which could cover the bandwidth extending that of a waveguide band. Other researchers have also demonstrated very wideband millimeter-wave amplifiers [10]. For example, an E-band amplifier has good noise and gain performance from about 55 GHz to 88 GHz, while Q-band covers the frequency range from about 27 GHz to 50 GHz. The bandwidth of the amplifiers is larger than any other component available for radiometer construction and, therefore, a part of it is "thrown away." Also, a part of the amplifier bandwidth could be useless for other reasons as, for example, interference or atmospheric opacity (55 to 68 GHz region in the example of an E-band amplifier in a ground-based radiometer). Consequently, a radiometer design of Fig. 1 should achieve much better sensitivity than a Dicke radiometer.

A comparable correlation radiometer would have to employ two amplifier chains, each of the bandwidth B_{RAD}. However, the design of a HEMT amplifier with optimal noise performance in bandwidth B_{RAD} usually allows for equally good performance in the bandwidth B_{CAL}, as long as B_{CAL} is chosen to be below B_{RAD} in frequency. The proposed radiometer would, therefore, employ half the HF hardware without loss of sensitivity. Also, achieving high isolation between channels in frequency domain seems to be much easier for the radiometer in Figure 1 than preventing the outgoing noise from one channel entering the other channel in the case of a correlation radiometer.

In some systems, it may be advantageous to interleave the calibration and signal channels, for example, two calibration channels each side of the signal channel or vice versa. Also, a system with several signal channels and one calibration channel should be possible.

III. An Example of the Possible Realization of Total Power Radiometer with Calibration in Frequency Domain

The proposed radiometer circuit, to the best of the author's knowledge, has never been built. In this section, it will be demonstrated that an example of Q-band radiometer with $\Delta T \approx 500\mu K\ sec^{1/2}$ could easily be built.

An example of the characteristics of a Q-band VLA-style amplifier is shown in Figure 2. The amplifier exhibits good gain and noise performance from 30-50 GHz, although it was designed for optimal noise performance in the 40-50 GHz range. Two amplifiers in cascade should provide sufficient gain for the noise of the detectors to have no impact on radiometer sensitivity.

The diplexers at the input and at the output of the amplifier should be of contiguous design [11]. An example of a waveguide diplexer of this type covering 3.5-5 GHz frequency range has been demonstrated in [12]. The characteristics of this diplexer are reprinted in Fig. 4 [12]. It is obvious that a simple scaling of the dimensions of this diplexer by a factor of 10 could yield a useful diplexer from the point of view of a Q-band radiometer. Assuming B = 6 GHz and T_{sys} = 25 K for a high altitude cryogenic instrument yields (eq. (4))

$$\Delta T = 550 \mu K\ sec^{1/2}$$

without the need for any chopping mechanism.

IV. Conclusions

This short note presented a new approach to wideband radiometers which performance is limited by random gain fluctuation of amplifiers. The proposed approach makes use of the observation that random gain fluctuations are fully correlated for different sub-bands within the amplifier band. This allows for the total power radiometer to be calibrated in frequency domain. In principle, there is no improvement in radiometer sensitivity if Dicke and correlation radiometers are compared with the proposed version under the condition of the same total bandwidth. However, the recent availability of very wideband, low-noise amplifiers, which bandwidth usually exceeds the bandwidth of other components available for radiometer construction, make the proposed solution rather attractive in practice. A design example of a Q-band radiometer is given which should yield the sensitivity of .5 mK $sec^{1/2}$ without the need for any switching. This approach could prove to be of value in addressing the total power instrumentation requirements for the GBT, MMA and VLA.

REFERENCES

[1] J. D. Kraus, *Radio Astronomy*, Cygnus-Quasar Books. 1986.

[2] R. H. Dicke, "The Measurement of Thermal Radiation at Microwave Frequencies," *Rev. Sci. Instruments*, vol. 17, pp. 268-275, July 1946.

[3] F. D. Drake and H. I. Ewen, "A Broadband Microwave Source Companion Radiometer for Advanced Research in Radio Astronomy," Proc. IRE, vol. 46, pp. 53-60, Jan. 1958.

[4] M. E. Tiuri, "Radio Astronomy Receivers," *IEEE Trans. Antennas and Progagation*, vol. AP-12, pp. 930-938, Dec. 1964.

[5] J. J. Faris, "Sensitivity of a Correlation Radiometer," *J. of Research of the National Bureau of Standards*, vol. 71C, pp. 153-169, June 1967.

[6] E. Wollack, "HEMT Gain Stability and Its Design Implications for Wideband Millimeter-Wave Receivers," *Rev. of Sci. Instruments*, vol. 66, pp. 4305-4312, Aug. 1995.

[7] N. Jarosik, L. Page, D. Wilkinson and E. Wollack, "Measurement of the Low Frequency Noise Properties of a 30 GHz HEMT Amplifier," Tech. Report No. 95955, Princeton University, Princeton, NJ, 1993.

[8] M. W. Pospieszalski *et al.*, "Q- and E-Band Cryogenically Coolable Amplifiers Using AlInAs/GaInAs/InP HEMT's, *Proc. 1995 IEEE MTT-S Int. Microwave Symp.*, Orlando, FL, pp. 1121-1124, May 1995.

[9] M. W. Pospieszalski, unpublished results, Nov. 1995.

[10] B. Kane, S. Weinreb, E. Fischer and N. Byer, "High Sensitivity W-Band MMIC Radiometer Modules," *Proc. 1995 MTT-S Microwave and Millimeter-Wave Monolithic Circuits Symp.*, Orlando, FL, pp. 59-62, May 1995.

[11] G. L. Matthaei, L. Young and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*, Artech House, Norwood, May 1980.

[12] J. F. Liang and K. A. Zaki, "CAD of Microwave Junction by Polynomial Curve Fitting," *Proc. 1993 IEEE MTT-S Int. Microwave Symp.*, Atlanta, GA, pp. 451-453, June 1993.

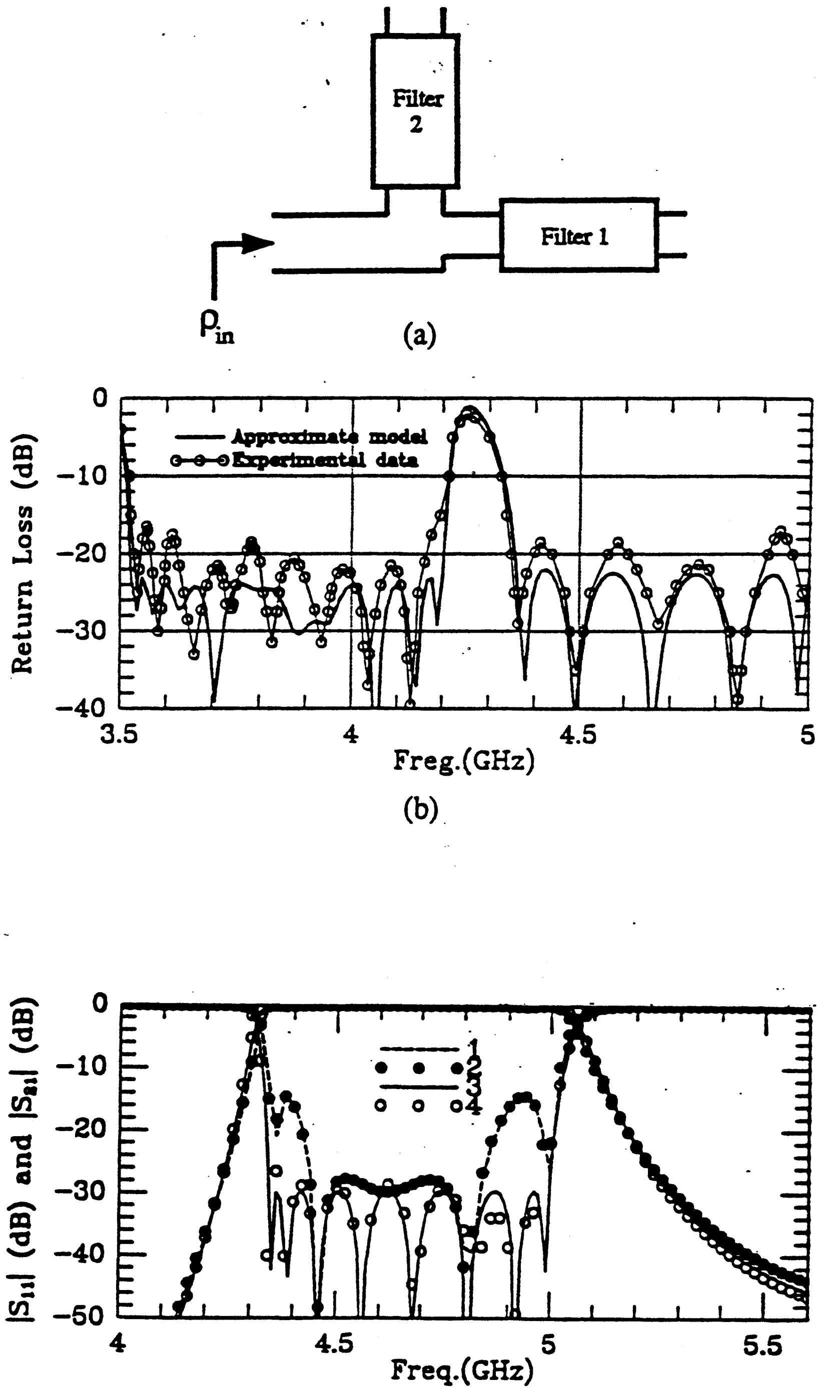

Fig. 3. The performance of an example of a diplexer in 3.5-5 GHz range [12]. A scaled version would be directly applicable to an example of the radiometer discussed in the text.

a) diplexer configuration

b) diplexer input return loss at common port

c) characteristics of 4.3-5 GHz filter

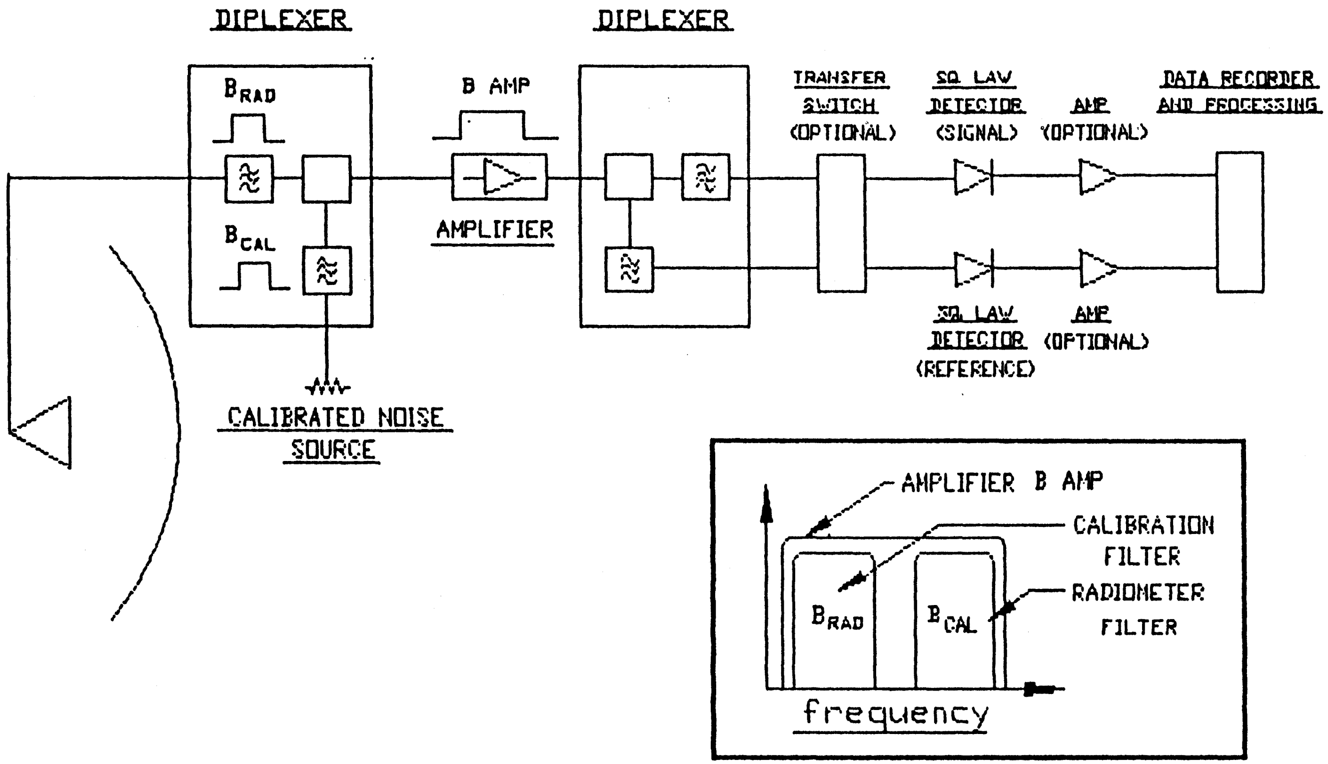

Fig. 1. Schematic of a total power radiometer with calibration in frequency domain.

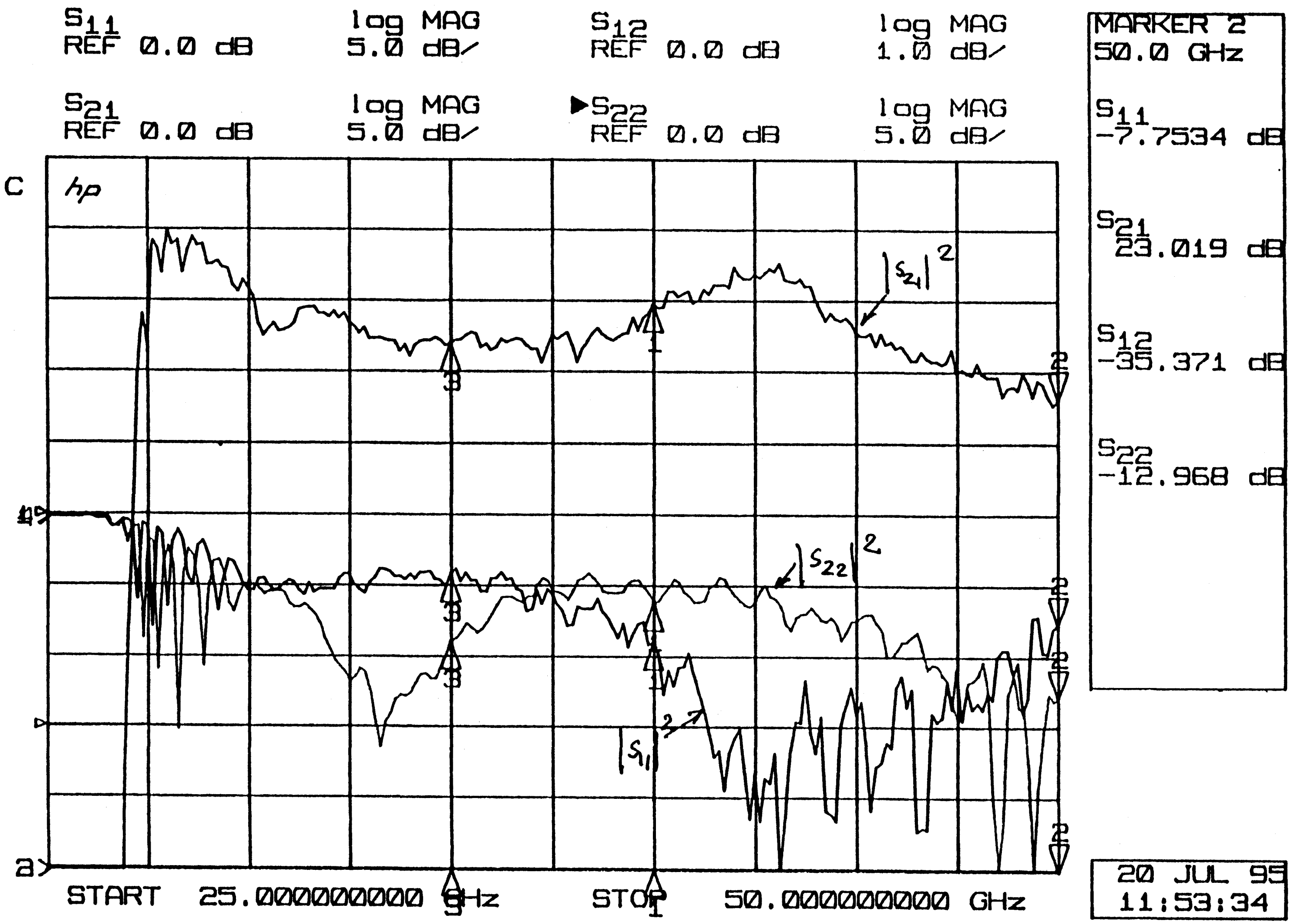

Fig. 2a. Gain and input and output return loss characteristics of a Q-band VLA-style amplifier at room temperature. A sudden gain drop at 27.5 GHz is due to the cut-off frequency of WR-22 waveguide.

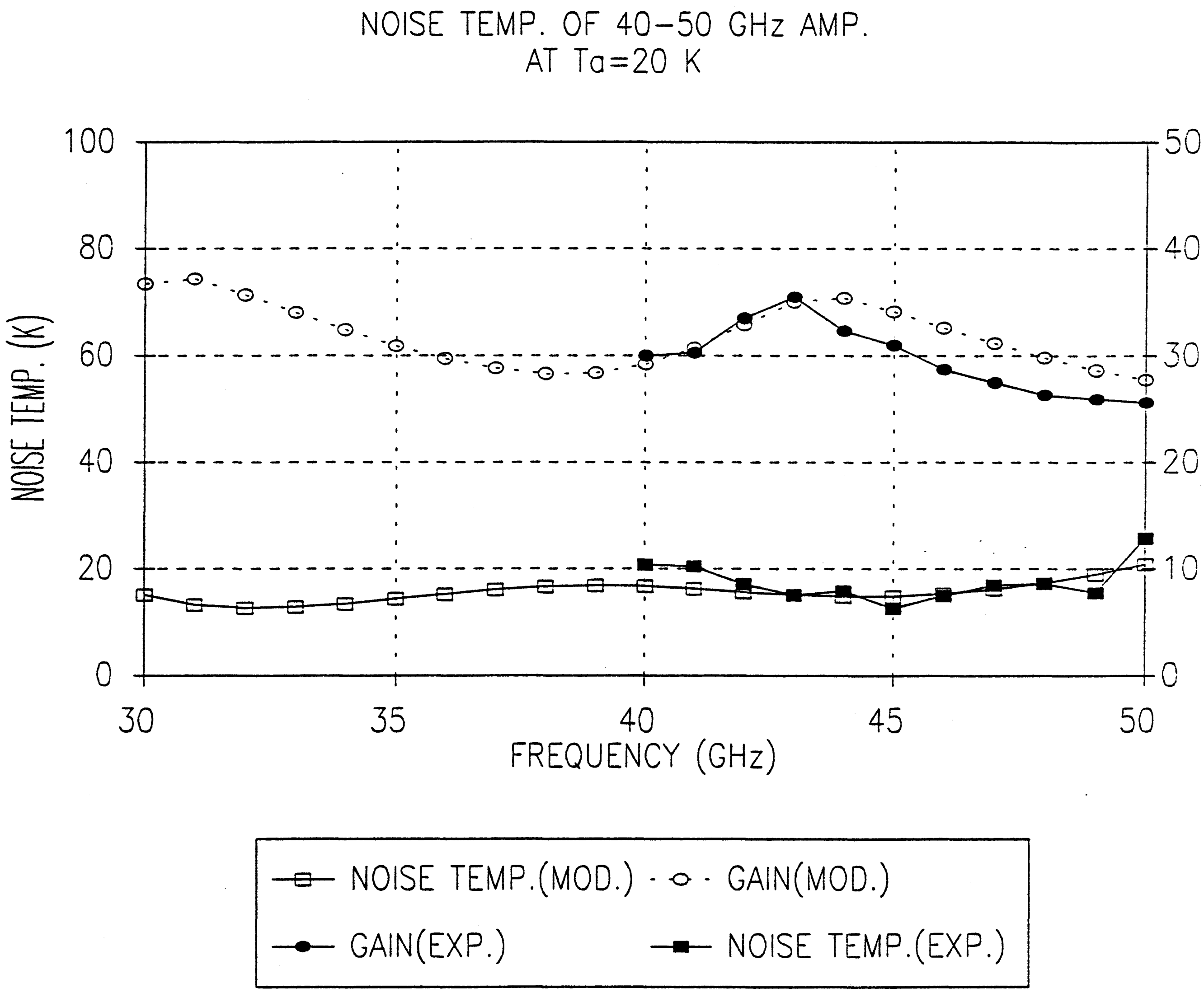

Fig. 2b. Predicted and measured gain and noise characteristics of a Q-band, VLA-style amplifier at 20 K ambient temperature.