N92-29374

Noise-Optimal Control of HEMT LNA's for Compensation of Temperature Deviations

C. MacCarley[1], J. J. Bautista, and P. A. Willis
Radio Frequency and Microwave Subsystems Section

Noise-optimal control of high-electron mobility transistor low noise amplifier (HEMT LNA) bias voltage and current values was achieved at room temperature. The performance metric maximized was the amplifier gain divided by the amplifier input noise temperature, G/T_e. Additionally, the feasibility of automating the initial determination of bias settings was demonstrated in the laboratory. Simulation models of an HEMT were developed from available measurement data, installed on a Sun SPARC I workstation, and used in investigating several optimization algorithms. Simple tracking-type algorithms, which follow changes in optimum settings if started at or near the global optimum point, produced the best performance.

Implementation of the optimization algorithms was performed using a three-stage Field Effect Transistor (FET) LNA and an existing test apparatus. Software was written to control the bias settings of the first stage of the LNA and to perform noise and gain measurements by using the test apparatus. The optimization control was then integrated with existing test software to create a master test and optimization program for test apparatus use.[2]

I. Introduction

The prime objective of this work was to develop a method to maintain optimal bias voltage and current values of an HEMT LNA as the physical temperature var-

ied. Since the input noise temperature of a multistage LNA is a function of both individual stage noise temperatures and gains, the optimal (i, v) values were defined to be those that maximize amplifier gain divided by the input noise temperature, G/T_e. These bias settings are temperature-dependent, and the amplifier performance degrades rapidly in the event of a cooling system failure. The amplifiers are normally cryogenically cooled to a physical temperature of 12 K.

---

[1] JPL Summer Facility Fellow, Radio Frequency and Microwave Subsystems Section.

[2] Source code for all programs discussed in this article is available in hard copy or electronic form from the authors by request.

Another objective was the automation of the initial in-laboratory setting of bias conditions for the LNA. The existing manual procedure is both time-consuming and possibly less than optimal due to practical limitations.

II. System Description

The experiment employed a three-stage HEMT LNA, an existing test apparatus, and an optimization algorithm realized as a program written in the IBM BASICA language. The procedure consisted of four steps prior to employing the test apparatus.

The first step was to characterize the HEMT LNA gain and noise temperature as a function of physical temperature for fixed bias conditions [1], as shown in Fig. 1. (Note that the curves of Fig. 1 are for fixed (i, v) points for each amplifier stage; their loci are obtained by varying the physical temperature.) The second step was to model the HEMT LNA to be optimally controlled as a $Zm + 2$ port system, as shown in Fig. 2.

The controller has available for feedback the system measurable output vector

$$y = \begin{bmatrix} T_e \\ G \\ T \end{bmatrix}$$

which generates a control vector

$$u = \begin{bmatrix} i_1 \\ \cdot \\ \cdot \\ \cdot \\ i_m \\ v_1 \\ \cdot \\ \cdot \\ \cdot \\ v_m \end{bmatrix}$$

such that some performance metric

$$\Psi = \Psi (T_e, G)$$

is maximized (or minimized).

Some forms (to be maximized) that jointly reflect the noise minimization and gain maximization objectives are

$$\Psi = \frac{G}{T_e} \quad \text{nonlinear} \tag{1}$$

$$\Psi = a_1 G + a_2 \left(\frac{1}{T_e} \right) \quad \text{linear, simple} \tag{2}$$

$$\Psi = \begin{bmatrix} G, \dfrac{1}{T_e} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} G \\ \dfrac{1}{T_e} \end{bmatrix} \quad \text{linear, quadratic} \tag{3}$$

The simple ratio Eq. (1) performance metric (a key figure of merit for receive systems) has been used in all subsequent work. The ratio is subject to internal parameter variations related nonlinearily to the operating temperature, T. Two system variables may be measured indirectly by power measurements: noise and gain. A third input variable, HEMT LNA temperature, may be measured directly.

The Zm control values must be generated for an m-stage LNA (six for a three-stage LNA: three bias voltages and three bias currents). The required model is a dc-bias-dependent operating point model of the amplifier circuit and solid-state devices, which includes internal noise sources. Model data at this level of detail are not available for the amplifier, although several constant bias trends with temperature are known from laboratory tests [1,2,3].

The third step was to write and exercise simulation models of an m-stage HEMT until a model was found whose input-output behavior was a good fit to the behavior of an actual HEMT. After studying available information on the relationship between drain current and voltage and the resulting noise and gain of an HEMT stage, a simple first-order model was derived. The drain bias current I_D is regulated by the gate source voltage V_{GS}, and the model incorporates this direct dependency.

The transconductance g_m of the isolated class A stage is expressed as a function of the gate-source voltage V_{GS}, the drain-source voltage V_D, and the junction temperature T

$$g_m = g_{m,max} \left(\frac{V_D}{V_{D,max}} \right)^{k_1} \left(1 - \frac{V_{GS}}{V_P} \right)^{k_2} \left(\frac{1}{\frac{T}{T_0} + 1} \right)^{k_3}$$

where k_i represents the experimentally determined constants, T_0 is the nominal temperature 300 K, V_P is the pinch-off voltage, $V_{D,max}$ is the maximum drain-source voltage, and $g_{m,max}$ is the maximum (most negative)

transconductance. Typical values for preliminary setup purposes were

$$k_1 = \tfrac{1}{2}$$

$$k_2 = \tfrac{1}{2}$$

$$k_3 = 1$$

$$V_P = -0.8 \text{ volts}$$

$$V_{D,max} = 5 \text{ volts}$$

$$g_{m,max} = -10 \text{ amps/volt}$$

As a first-order estimate, the gain G and noise temperature T_e are functions of the amplifier transconductance g_m alone

$$G = k_4 g_m$$

$$T_e = T_{e,min} \sqrt{\frac{g_{m,max}}{g_m}}$$

where typical values were used for the constants:

$$k_4 = -1$$

$$T_{e,min} = 10 \text{ K}$$

Hard constraints on the controllable parameters were

$$0 < V_D \leq 5 \text{ volts}$$

and

$$-0.8 \leq V_{GS} \leq 0 \text{ volts}$$

The fourth step was to select the figure of merit and optimization algorithm and apply them to the simulated system. The simple gain-to-noise linear ratio ($\Psi = G/T_e$) was used. A simple tracking-type optimization algorithm was adopted. The operating points immediately surrounding the current point (assumed optimum) are searched for relative optimality. Thus, variations in the true optimum point (e.g., due to temperature changes) are faithfully tracked. The optimization method uses no knowledge of the actual system or the manifold of the performance metric. The system is treated purely as a black box. While this method is very inefficient for general optimum locating problems, it is a reasonable choice for problems of this type, in which the search is initiated at or near the known global optimum, and the objective is to track slow changes in the location of that optimum point.

Each iteration of 2^n points is tested by perturbing the values of each parameter, measuring gain and noise, and calculating the performance metric. For the simple case ($n = 2$), only two parameters V_D and V_{GS} are involved. The four adjoining points tested are

$$V_D \pm \Delta V_D$$

and

$$V_{GS} \pm \Delta V_{GS}$$

ΔV_D and ΔV_{GS} may be variable in size, starting at a large perturbation and decreasing as convergence to the optimum proceeds.

For the first-order circuit model, the simulation reliably located the optimum at the maximal limits $V_{GS} = 0$ and $V_D = 5.0$ volts. This was expected, since the simple relationships used for G and T_e are maximized and minimized, respectively, by increasing g_m. Thus, the optimization seeks to maximize g_m, which occurs at the limiting values of V_D and V_{GS}. Clearly, a more sophisticated model for the HEMT amplifier stage is needed that specifically incorporates higher order effects. These effects are not apparent from simple device physics and dc observations.

A simple second-order modification of the noise relationship was tested:

$$T_e = T_{e,min} \left[\left(\frac{g_{m,max}}{g_m} \right)^{1/2} + k_6 g_m^2 \right]$$

where a range of values for k_6 was tested. For the case of $k_6 = 0.2$, the optimal values of V_{GS} and V_D were found to be 0 and 4.3 volts, respectively. The optimum now occurs away from the external limits.

It is doubtful that an actual amplifier stage behaves according to this model, especially when operated at cryogenic temperatures. Also, stage-to-stage interactions in a multistage LNA would further raise the level of model complexity. The task of determining an accurate higher

order model would be a major project alone, beyond the scope and time limitations of this work. It was concluded that bias optimization, in general, was potentially beneficial and worthy of further study using actual hardware, which is described in the remainder of this article.

III. Experimental Apparatus

An existing noise/gain test apparatus (JPL Automated Test Bench) was used for data acquisition and control of a three-stage Field Effect Transistor (FET) LNA. These experiments were conducted at room temperature. This apparatus provided the ability to measure frequency-specific amplifier noise and gain, and included two digital-to-analog converters for computer control of the first-stage drain current and voltage. The second- and third-stage biases were manually set to fixed values. A block diagram of the test apparatus is shown in Fig. 3.

The JPL automated bench test software (BENCH.BAS) written in IBM BASICA served as the LNA monitor and controller. Using the interface routines from this software, a program (OPT.BAS) was written in BASICA which used this apparatus to optimize the first-stage drain current and voltage with respect to the previously described performance metric, G/T_e. Eventually, all the features of BENCH.BAS were incorporated into OPT.BAS, which resulted in a single integrated test and first-stage optimization package for multistage LNA's. A user-friendly tutorial-type interface was also added to assist users in setting up and calibrating the apparatus and performing tests or optimization. (Use of the program is largely self-explanatory. Type "OPT" and follow the prompts and help menus. Complete documentation is also available in the text file OPT.MAN.)

The program makes power and gain measurements by using formulas based on the derivations below. In these, N is a physical power measurement made by the power meter circuit of the bench apparatus; T_e is a noise temperature, both in units of power and expressed as absolute temperature in K; G is power gain, unitless and linear (not in decibels); the superscript H refers to the hot noise source; C refers to the cold noise source; the subscript F refers to the postamplifier (including internal amplification in the bench apparatus); and the subscript e refers to the amplifier under test.

During calibration, only the postamplifier is connected in the signal path between the noise sources and the power meter. Power measurements in this configuration are denoted by the subscript 2. A hot and a cold power measurement is made for each anticipated test frequency

$$N_2^H = (T_H + T_F) G_F$$

$$N_2^C = (T_C + T_F) G_F$$

$$\Delta N_2 = N_2^H - N_2^C = (T_H - T_C) G_F$$

During a measurement or optimization operation, with the amplifier under test in the signal path ahead of the postamplifier, another hot and cold power measurement (denoted by the subscript 1) is made at each point:

$$N_1^H = ((T_H + T_e) G_e + T_F) G_F$$

$$N_1^C = ((T_C + T_e) G_e + T_F) G_F$$

$$\Delta N_1 = N_1^H - N_1^C = (T_H - T_C) G_e G_F$$

The power gain of the amplifier under test is calculated from

$$\frac{\Delta N_1}{\Delta N_2} = G$$

The power ratio Y, or Y factor, is defined as

$$Y = \frac{N_1^H}{N_1^C} = \frac{((T_H + T_e) G_e + T_F) G_F}{((T_C + T_e) G_e + T_F) G_F}$$

This expression is solved for the noise contribution of the amplifier under test (referenced to its input) in terms of the previous power measurements and the known source load temperatures T_H, T_C, and the noise temperature contribution of the postamplifier. The amplifier noise temperature is given by

$$T_e = \frac{T_H - Y T_C}{Y - 1} - \frac{T_F}{G_e}$$

The previously simulated simple tracking optimization algorithm was employed, and the size of the perturbation for each parameter was made adaptive (in the latest version). As the algorithm converges closer and closer to the optimal operating point, the bias conditions are perturbed less and less until the optimum is reached. The stopping criteria tests for a reduction of the perturbation parameters

to a useful lower limit. This approach aids in the accuracy of the optimization, hopefully without compromising the ability to track slowly varying changes in the optimum point due to temperature variation. If the optimal point shifts too rapidly, a loss-of-lock situation might temporarily occur due to the slowed tracking ability of the optimization with the smaller parameter perturbation limits. Since no temperature dependency tests were performed with the test apparatus, it was not possible to determine if this was a legitimate concern.

Using the apparatus and software, the three-stage FET LNA operating at room temperature (300 K) and 2.3 GHz was tested and bias optimized. It was not possible to test for temperature effects on the optimal bias settings, or the optimal tracking performance. Rather, tests were performed using the apparatus to locate the optimal from arbitrary initial points in the bias condition vector space.

For starting points close to the global optimum and small initial search increments, the optimal bias drain voltage and current are usually found within 15 minutes of run time, at approximately 2.9 volts and 12 mA, respectively. For initial search increments greater than ±1 volt for V_D or ±5 mA for I_D, local optimums with performance metrics less than the global optimum were sometimes located. Even though the search increment is reduced by the algorithm during convergence to the optimum, large initial search increments typically resulted in random results. The reported G/T_e figure at each point is also very sensitive to the initial calibration and hot noise source temperature measurement, which typically varied as much as 5 percent between successive runs at identical conditions.

Two significant problems were encountered using this apparatus. The first was the problem of noise. For each test point, two power measurements are made: one with a room-temperature noise source connected to the input of the amplifier under test, and the other with a liquid nitrogen–cooled "cold" noise source at the input. The sources are selected by an electromagnetically actuated switch controlled by the program. The two power measurements and their difference provide the necessary information for calculating the noise generated by the amplifier itself, as well as the amplifier gain.

Since the progress of the optimization requires very accurate noise and gain measurements at each test point, even a small error component in the power measurements could seriously affect the progress of the optimization toward a global optimum. The result is a "random walk" in some neighborhood of the optimum, or convergence to a

false optimum due to an erroneously high-gain or low-noise measurement.

The solution to this problem was to take several measurements at each point and average them together. The accuracy of the performance metric calculated at each point was substantially improved using this technique, at the expense of a proportional increase in the time required to converge to an optimum.

The second problem was one of convergence time. Upon each iteration, 2^n points must be tested. Then, several power measurements must be made at each point to form the average. The optimization process could become lengthy if one started at a point far from the optimum. The switching time of the electromechanical noise source selector switch and the integration time of the rms power meter circuit are the underlying time-consuming factors. By replacing the electromechanical switch with an electronically switchable noise source (or sources), and employing faster power measurement methods, the convergence time of the optimization could be proportionally reduced.

IV. General Considerations for Use of LNA Gain/Noise Optimization

There seem to be two general categories of uses for LNA gain/noise optimization: off-line optimization with open-loop compensation during actual service, or on-line optimization using closed-loop compensation. There are advantages and disadvantages associated with each approach.

A. Off-Line Method

Prior to actual service, optimum bias conditions for the LNA are determined at each temperature. An appropriate optimization algorithm is used at several fixed temperature settings to determine the (not necessarily unique) values of i_j and v_j, $j = 1, \cdots, m$, which maximize the given performance metric $\Psi(T_e, G)$ for the actual system.

The lack of a complete system model requires the use of the model-independent optimization method described in the previous section. Such optimization methods are characterized by search techniques that start from some initial parameter setting and converge to a global optimum. Since the actual system rather than a mathematical model is used, convergence may take a considerable amount of time.

Another limitation of search-based optimization algorithms is possible failure to converge or convergence to a local rather than global optimum. The problem is intrinsic to deterministic approaches. Alternatively, a Monte Carlo method might be applied, one that randomly accumulates knowledge about the system and identifies the global optimum. This approach increases the run time of the algorithm. Excessive run times could be expected for an eight-parameter problem (assuming that four stages are optimized), as well as for the practical problem of avoiding possible damage to the LNA by eliminating any unusual bias combinations.

Fuzzy logic methods were also considered for the optimization and/or control problem due to limited knowledge about the system to be controlled. The simplicity of fuzzy methods, which use a heuristic approach to control law construction, was attractive. When these methods are applied to the off-line optimization process, some rule generation process, such as differential competitive learning (DCL) [3,4], might be used to generate a rule base for a fuzzy optimization algorithm (if one could be synthesized). The rule base may be considered equivalent to the optimum bias lookup table.

From an input/output perspective, fuzzy logic controls simply map an m-vector of inputs to an r-vector of outputs. The mapping is nonlinear and no different from conventional nonlinear full-state feedback controls from an input/output point of view. The novelty and power of the method derive from the relative simplicity by which the input/output mapping is constructed by using heuristic information rather than precise models [5].

It is uncertain if an adequate number of sensed system variables from the LNA are available for the use of fuzzy control methods. Fuzzy logic controls seem to be most successful in situations where sufficient measurable system variables are accessible, and a smaller number of control inputs and outputs must be generated. In the present application, there are a maximum of three measurable system variables (noise, gain, and temperature), and as many as eight control outputs to be determined, each with synergistic effects on the system. Fuzzy controls are typically suboptimal. The degree of optimality of the control is determined by the accuracy of the off-line rule-generation process.

The only area of applicability of fuzzy methods to this task seems to be in the formation of the rule base or stored optimum bias information table for the off-line optimization or the adaptive optimization/control approaches.

Minimum-knowledge learning procedures developed for fuzzy logic control programming might increase the efficiency of generating the tables which characterize the system.

Regardless of the optimization method, the result is a simple stored lookup table with one input T and up to eight outputs (all bias voltages and currents). This table is then used for real-time setting of the bias conditions as a function of T when the LNA is in actual use.

A general limitation of this approach is the potential that other disturbances and parameter variations could alter the validity of the open-loop table, or rule base, between the time it was determined and the time that it is actually used. Another limitation is that the amplifier must be taken off-line and run through a controlled temperature and possibly time-consuming optimal bias determination procedure. With the objective of testing the amplifier under conditions as close to actual as possible, the procedure is most accurately done on the actual field installation, although laboratory characterization may be the only practical approach.

The difficulties associated with the nonlinear multiparameter optimization have already been addressed, and it should be noted that these difficulties are common to both off-line and on-line optimization methods.

The noteworthy advantage of the off-line approach is that the system would not be disturbed during actual use by an optimization search routine. Measurement of noise and gain might also be more easily (or possibly only) accomplished off-line rather than during critical real-time usage.

B. On-Line Method

The amplifier is continuously optimized during actual in-field use. Starting with known optimum bias settings at the normal operating temperature (e.g., 12 K), the bias conditions are continuously optimized in such a way as to maximize $\Psi(T_e, G)$. A requirement of this approach is that both T_e (noise) and G (gain) are measurable in real time without adversely disturbing the normal operation of the receiving system.

Real-time optimization methods for partially or completely unknown systems involve the use of search or optimum tracking algorithms. These require that each input parameter (bias voltages and currents, in this case) of the actual system be periodically perturbed, and the measurable components of the performance metric (noise and

gain, in this case) be sampled upon each iteration. Herein lies a key limitation of this approach, since the actual system might not tolerate such periodic small perturbations of all parameters. Obviously such parameter variations would have to be kept as small as possible within the precision limits of the noise and gain measurements. Temperature feedback is not required, since the method would continuously correct for all (slow) disturbances and parameter variations not limited to temperature effects alone. If started at or near an optimum point, this approach could be expected to track the moving optimum as the operating temperature varied.

The most notable limitation of this method is the need to perturb bias conditions during actual operation. This may or may not be acceptable, depending on the size and tolerability of the perturbations. Also, for this approach to successfully maintain an optimum, all disturbances and parameter variations (mainly temperature related) must change at a sufficiently slow rate to permit tracking of the optimum by the algorithm. An abrupt change (e.g., one due to a change made manually by the operator) could leave the tracking algorithm lost, seeking the nearest local optimum, off the optimal locus for temperature variation. The inefficiency of the search algorithm could make this a nontrivial concern, especially if the available real-time computational bandwidth is limited.

Furthermore, there is no guarantee that by starting from a global optimum for the normal operating temperature, the temperature-optimal locus would continue to be globally optimal. A quantum change in bias settings might be required to hop to a new global optimum at some temperature. However, such an abrupt change in bias conditions may not be tolerable due to a need for glitch-free reception, especially during critical data acquisition events.

The clearest advantage of the on-line approach is that the actual system at the time of operation is optimized for best noise/gain performance. If the starting point is a global optimum for the normal temperature, and the system itself is continuous with temperature variations, the bias parameters could be expected to change continuously and smoothly, maintaining at least a locally optimal setting as the temperature or other amplifier parameters slowly vary. Finally, no downtime is required for off-line optimization table generation (or rule learning).

C. Adaptive Off-Line and On-Line Methods

Another approach is a combination of both on-line and off-line optimization and control methods. Off-line char-

acterization is used to determine an initial optimal operation table. During actual operation of the amplifier, an on-line optimization algorithm continuously updates the table based on real-time tracking of the optimum and some long-term adaptive strategy. Temperature feedback is required.

Abrupt system changes are not tolerated, since the controller contains stored information about the previous optimal parameter settings for any given temperature. The learning capability of the controller frees it from the long-term accuracy limitations of the off-line optimization/open-loop control approach.

The problem of on-line parameter perturbation remains, and the need for preliminary determination of the optimal parameter table or rule base also exists. This approach is the most robust, probably the most effective, but also the most complicated to put into actual practice.

V. Conclusions

A computer simulation of a generic HEMT-based multistage LNA has been completed by utilizing a first-order approximate model of a single stage at room temperature. The simple analog ratio of the amplifier gain to the amplifier noise temperature was selected as a readily measurable optimization metric.

Several optimization methods for unknown systems were evaluated with the aid of the simulation. These included fuzzy logic control methods in which a temperature compensation table is implemented as a fuzzy rule base. The best results for this application were achieved with simple tracking-type optimization algorithms. The simulation results provided justification for proceeding with work on actual hardware.

A program, OPT, was written in BASICA under DOS 3.3 to control the JPL Automated Bench for use as a first-stage bias optimization apparatus. The previous BENCH software was merged with OPT to create a single LNA test and optimization package for the apparatus. User-friendly features were incorporated to assist operators in performing calibration, amplifier testing, and optimization.

A three-stage FET LNA operating at room temperature and 2.3 GHz was tested and bias optimized. For starting points close to the global optimum, the optimal bias drain voltage and current were consistently found within a few minutes of run time, at approximately 2.9 volts and

12 mA, respectively. Noise on the power measurements required that all optimization test points be averaged over at least five iterations. For initial search increments greater than ±1 volt for V_D or ±5 mA for I_D, local optimization with performance metrics less than the global optimum were sometimes located.

Bias optimization for maximizing the gain-to-noise ratio of an LNA appears to be feasible in the laboratory, as does construction of temperature compensation look-up tables for bias parameters. The applicability of on-line bias optimization during actual service of an LNA remains uncertain, and further experimentation is planned.

References

[1] K. H. Duh, W. Kopp, P. Ho, P. Chao, M. Ko, P. Smith, J. Ballingall, J. Bautista, and G. Ortiz, "32-GHz Cryogenically Cooled HEMT Low-Noise Amplifier," *IEEE Transactions on Electron Devices*, vol. 36, no. 8, pp. 1528–1535, August 1989.

[2] H. Fukui, "Optimal Noise Figure of Microwave GaAs MESFET's," *IEEE Transactions on Electron Devices*, vol. 26, pp. 1032–1037, July 1979.

[3] B. Kosko, "Neural Networks and Fuzzy Systems," Englewood Cliffs, New Jersey: Prentice-Hall, 1992.

[4] S. Chiu, S. Chand, D. Moore, and A. Chaudhary, "Fuzzy Logic for Control of Roll and Moment for a Flexible Wing Aircraft," *IEEE Control Systems*, vol. 11, pp. 42-48, June 4, 1991.

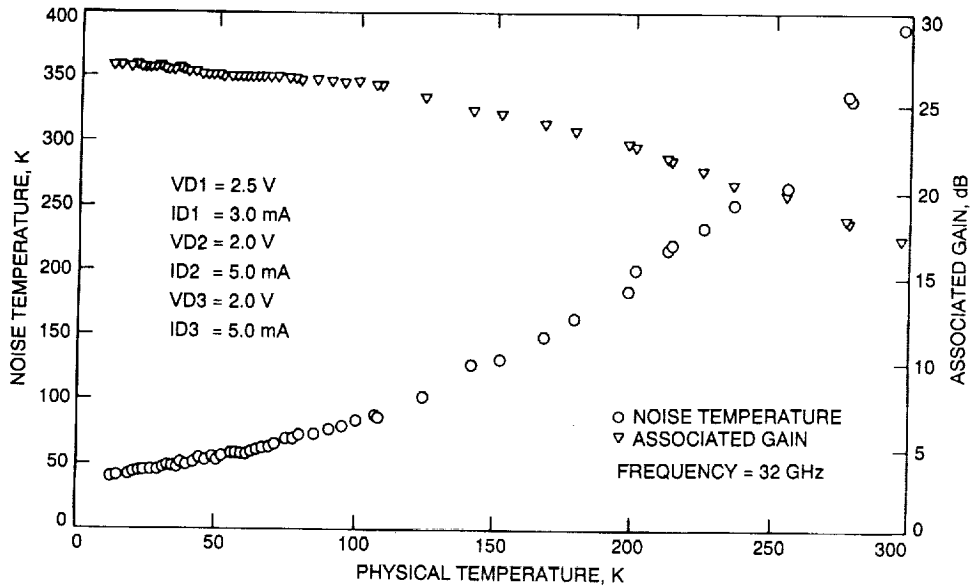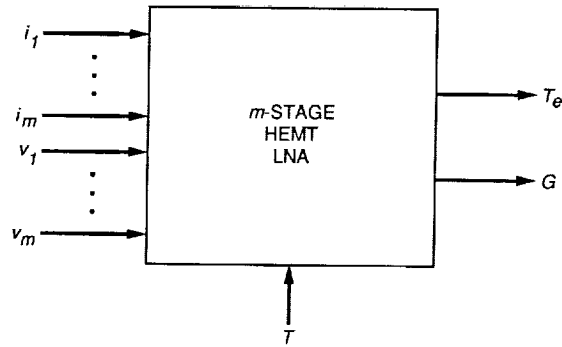[5] K. Self, "Designing with Fuzzy Logic," *IEEE Spectrum*, pp. 42, 44, and 105, November 1990.

Fig. 1. Temperature dependency of noise and gain for a three-stage HEMT LNA.

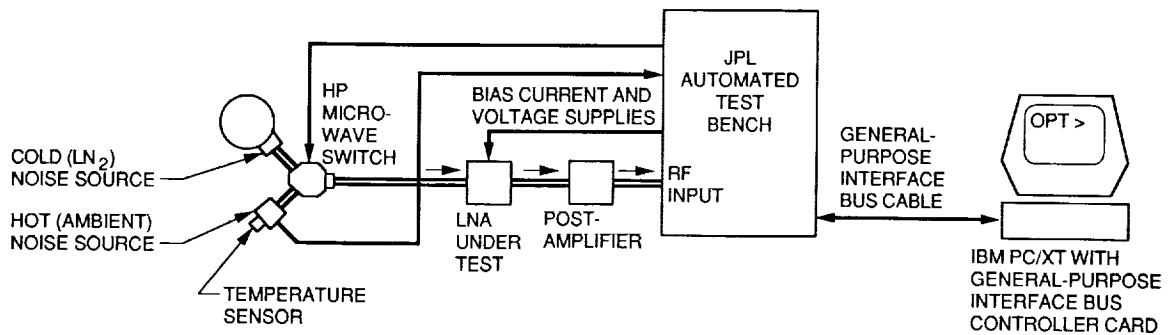| m | NUMBER OF AMPLIFIER STAGES |
i_n	BIAS CURRENT OF STAGE n
v_n	BIAS VOLTAGE OF STAGE n
T_e	EQUIVALENT AMPLIFIER INPUT NOISE TEMPERATURE
G	OVERALL AMPLIFIER GAIN
T	OPERATING TEMPERATURE (ABSOLUTE)

Fig. 2. System to be controlled or optimized.

Fig. 3. LNA test and optimization apparatus.