

- [13] A. S. Omar and K. Schünemann, "Transmission matrix representation of finline discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, p. 765, Sept. 1985.
- [14] R. Mittra and S. W. Lee, *Analytical Techniques in the Theory of Guided Waves*. New York: Macmillan, 1971.
- [15] R. E. Collin, *Field Theory of Guided Waves*. New York: McGraw-Hill, 1960.
- [16] T. Itoh, *Numerical Techniques For Microwave And Millimeter-Wave Passive Structures*. New York: Wiley 1989.
- [17] J. D. Wade and R. H. MacPhie, "Scattering at circular-to-rectangular waveguide junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, p. 1085, Nov. 1986.
- [18] R. Vahldieck, B. Varailhonde la Filolie, and P. Aubry, "Rigorous field theory analysis of coax transitions and filters," in *Proc. MIOP '90* (Stuttgart), 1990, p. 5A.5.

High-Performance HEMT Amplifiers with a Simple Low-Loss Matching Network

R. Peter, M. V. Schneider, and Y. S. Wu

Abstract—We report on the design and performance of a K-band HEMT amplifier whose passive circuit consists of low-loss suspended stripline elements. The single-stage amplifiers were built at 4 GHz and 22 GHz by using readily available commercial HEMT devices. In the desired frequency range from 21 to 23 GHz for the high-frequency design, the best spot noise temperatures were 150 K and 65 K at 21.5 GHz for room and liquid nitrogen temperatures, respectively.

I. INTRODUCTION

Recent advances in the performance of HEMT's make it possible to use the devices in low-noise applications, such as front ends for high-data-rate communications links or remote sensing circuits, instead of complex and expensive maser systems [1]–[4]. The main objective of the work described in this paper was to design and construct an amplifier at 22.235 GHz for a water vapor radiometer. Another objective was to use inexpensive and readily available chips embedded in a low-loss suspended microstrip structure (air line) instead of the more widely used coaxial air line design [5], [6].

Encouraged by the good results of a cryogenic IF amplifier at 4 GHz consisting of an air line structure, we used a similar design at 22 GHz. The absence of dielectric losses and a stripline to waveguide transition are the main features of our low-loss tuned circuit design. Since these circuits do not have a substrate, problems with thermal contraction of different materials will not occur when the amplifier is cooled. The air line design offers higher flexibility in making changes and reduces turnaround times for achieving optimized noise performance.

Manuscript received May 22, 1990; revised April 2, 1991. This work was supported by the Swiss Department of Economy under Contract EVD-1735.1.

R. Peter is with the Institute of Applied Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland.

M. V. Schneider and Y. S. Wu are with AT&T Bell Laboratories, Holmdel, NJ 07744.

IEEE Log Number 9101021.

Furthermore, no expensive substrates or precision photolithographic facilities are necessary.

II. AMPLIFIER DESIGN

A schematic drawing showing the top view of the single-stage K-band amplifier is displayed in Fig. 1. The microstrip quarter-wave transformer consists of a milled gold-plated brass strip (0.15 mm thick) which is supported by two 0.25-mm-thick quartz slabs. The end of the low-impedance section is tapered in order to reduce the capacitive interaction between the air line and the grounded ridge in which the HEMT chip (Fujitsu FHR02X) is embedded (Fig. 2). In order to achieve a low parasitic inductance we used short gold wires with a diameter of 18 μ m to connect the chip to the circuit by thermocompression bonding.

The input and output matching networks do include the air line–waveguide transitions, which are realized by a probe (50 Ω line section) extending 2.6 mm into the waveguide [7], [8]. The transitions have been tested with a 50 Ω trough line which is 1.1 mm wide and 0.25 mm above the ground plane of the housing. We measured a total insertion loss of the trough line of 0.5 dB (i.e., approximately 0.25 dB per transition) over a bandwidth of 2 GHz. Since this simple transition has a relatively narrow bandwidth, optimum tuning can be obtained at other center frequencies in the K band by adjusting the broad-band backshort.

The low-impedance sections of the transformers optimized for room temperature operation have a width of 2 mm and a length of 4.5 mm at the input and a length of 5.75 mm at the output, respectively. For the bias circuits a 90° radial stub on a 0.25-mm-thick alumina substrate was used with a $\lambda/4$ high-impedance bond wire. In order to improve the stability of the amplifier we added a 50 Ω series resistor and a shunt capacitor of 10 pF to the bias network and filled the cavity of the bias network with absorber material. In the following section we consider a simple calculation of the different noise contributions and the associated loss of the input matching circuit.

The noise performance of an amplifier is determined by the ohmic loss of the matching network to the input of the transistor and by the noise characteristics of the transistor. The noise temperature of an HEMT amplifier with a lossy input matching network can be expressed as the sum of two terms:

$$T_A = (L - 1)T_L + LT_{\text{HEMT}} \quad (1)$$

where L is the ohmic loss factor, T_L is the physical temperature of the network, and T_{HEMT} is the noise temperature of the transistor referred to the input of the matching network. T_{HEMT} is characterised by four noise parameters. T_{MIN} , the minimum noise temperature; $Z_{\text{OPT}} = R_{\text{OPT}} + X_{\text{OPT}}$, the optimum source impedance; and g_N , the noise conductance. Over a narrow bandwidth, T_{HEMT} of a well noise matched transistor is approximately equal to T_{MIN} .

The total loss, L , of the matching circuit and transition at 22 GHz can be calculated with $T_{\text{HEMT}} = 105$ K (from the manufacturer's data sheet for the FHR02X) and the measured amplifier noise temperature $T_A = 170$ K at room temperature ($T_L = 300$ K) using (1).

Table I shows the estimated losses of the input circuit (including the transitions) for the 22 GHz amplifier and the 4 GHz amplifier (similar construction).

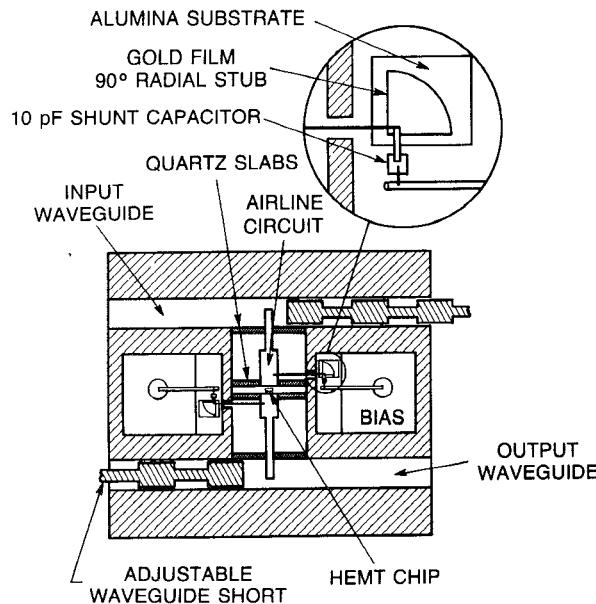


Fig. 1. Schematic drawing of the K-band amplifier with waveguide input and waveguide output port. The microstrip-air line circuit is connected by 18 μm bond wire with the bias network consisting of a series resistor, shunt capacitor, and radial stub on alumina substrate. The movable back-shorts allow fine-tuning of the transition.

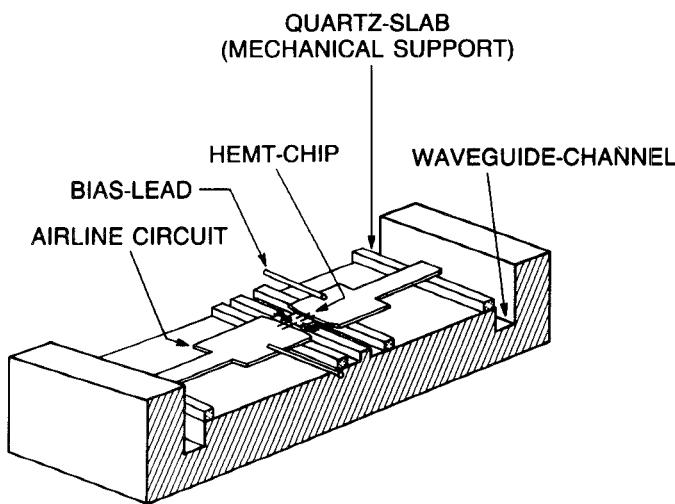


Fig. 2. Details of the microstrip-air line, which is supported with quartz slabs.

Since the noise parameters depend on frequency [9] and temperature [5], [10], the first experimental approach of the air line design was a 50Ω line with movable gold-plated brass tabs ($\approx 2 \times 1 \text{ mm}$). This tunable design allowed easy corrections of the matching networks in the cooled operation mode. We used this tuning technique successfully in a matching network of a cryogenic amplifier at 4 GHz. Even if the reproducibility and the matching are not as good as with the quarter-wave transformer, the method described above is useful for a rapid optimization of an amplifier test circuit.

However, a theoretical approach for the CAD optimized quarter-wave transformer of a cryogenic design can be obtained by the noise model proposed by [10]. The optimum noise resistance, R_{OPT} , of the FHR02X at 12.5 K according to [10] and

TABLE I
LOSSES OF THE INPUT CIRCUIT FOR TWO SIMILAR AIR LINE AMPLIFIERS

Parameter	4 GHz FHR02FH	22 GHz FHR02X
T_A (meas.)	40 K	170 K
G in dB (meas.)	13	6.2
Gain factor G (meas.)	20	4.17
T_{Min} (data sheet)	24 K	105 K
Loss in dB (calc.)	0.2	0.65
Loss factor L (calc.)	1.05	1.16

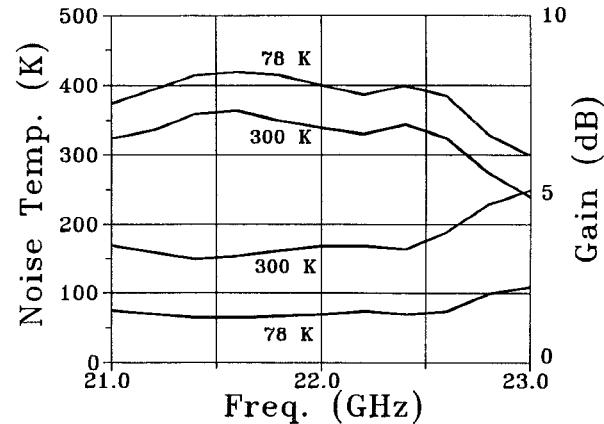


Fig. 3. Gain and noise performance at room temperature and 78 K. The two upper curves represent the gain and the two lower curves indicate the noise temperature of the amplifier.

[11] will decrease to approximately half of the room-temperature value, while the reactance, X_{OPT} , is not much different at low ambient temperatures. Thus for a cryogenic design, the width of the quarter-wave transformer has to be increased in order to match Z_{OPT} .

III. RESULTS

The single-stage amplifier has been experimentally optimized by using an automatic noise figure and gain measurement system. A calibrated noise source (HP 346C) was connected to the amplifier input through a broad-band isolator in order to minimize measurement errors caused by reflections. For an exact calibration at the input of the amplifier, the losses of the isolator, noise source transition, and waveguide section at different ambient temperatures are taken into account.

Shifting of the noise figure minimum was achieved by adjusting the back-short position of the waveguide transition. However this changes only the transition tuning and does not affect the quarter-wave transformer, which is designed for 22 GHz (room temperature). Nevertheless, at 18 GHz (outside the desired frequency range) a noise figure of 1.5 dB (120 K) and a gain of 8.5 dB (room temperature) were obtained. The results for the desired frequency range of 21 to 23 GHz are given in Fig. 3.

By cooling the amplifier with liquid nitrogen, the noise figure decreases to 1.0 dB (75 K) at 22 GHz. At 18 GHz we measured a spot noise figure of 0.7 dB (50 K) with a different back-short position. The bias conditions for low noise operation were 2.5 V/12 mA at 300 K and 2.5 V/8 mA at 78 K, respectively.

We also used a JS 8900 (Toshiba) HEMT instead of a FHR02X. Although the stability of the JS 8900 was better, the noise figures were 2.3 dB (200 K) and 1.05 dB (80 K) at room temperature and 78 K, respectively.

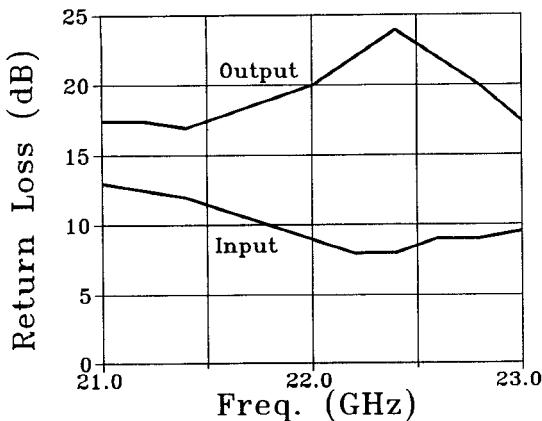


Fig. 4. Input and output return losses at room temperature without isolator.

The input return loss and output return loss are shown in Fig. 4 for the room-temperature operation mode. Typical for a low-noise amplifier is a bad input return loss because Γ_{OPT} and Γ_{11} of the transistor are not identical. Owing to the partly correlated gate and drain noise sources in the FET itself, noise cancellation occurs by reflections at the slightly mismatched input. However, for a better input match an isolator may be necessary.

Our results indicate that in the range between 21 and 23 GHz the waveguide-air line design is slightly superior to our more conventional microstrip circuit on an alumina substrate (same transistor) including coaxial transitions.

ACKNOWLEDGMENT

The authors wish to thank J. Siegenthaler and B. Eicher, Swiss PTT, for providing the microwave measurement equipment and their help during the measurements. We are also

indebted to C. Tran for bonding the HEMT chips and to K. Schwartz (both with AT&T Bell Laboratories) for machining the housings.

REFERENCES

- [1] G. K. H. Duh *et al.*, "Ultra low noise cryogenic high-electron-mobility transistors," *IEEE Trans. Electron Devices*, vol. 35, pp. 249-254, Mar. 1988.
- [2] M. W. Pospieszalski, S. Weinreb, R. D. Norrod, and R. Harris, "FET's and HEMT's at cryogenic temperatures—Their properties and use in low noise amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 552-560, Mar. 1988.
- [3] S. Weinreb, M. W. Pospieszalski, and R. Norrod, "Cryogenic, HEMT, low noise receivers for 1.3 to 43 GHz range," in *1988 MTT-S Int. Microwave Symp. Dig.*, May 1988, pp. 945-948.
- [4] U. K. Mishra, A. S. Brown, M. J. Delaney, P. T. Greiling, and C. F. Krumm, "The AlInAs-GaInAs HEMT for microwave and millimeter-wave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1279-1285, Sept. 1989.
- [5] S. Weinreb, "Low-noise cooled GASFET amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1041-1054, Oct. 1980.
- [6] M. W. Pospieszalski *et al.*, "Noise parameters and light sensitivity of low-noise high-electron-mobility transistors at 300 and 12.5 K," *IEEE Trans. Electron Devices*, vol. ED-33, pp. 218-223, Feb. 1986.
- [7] R. H. Knerr, "A new type of waveguide-to-suspended stripline transition," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 192-194, Mar. 1968.
- [8] B. Glance and R. Trambarulo, "A waveguide-to-suspended stripline transition," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 117-118, Feb. 1973.
- [9] A. F. Podell, "A functional GaAs FET noise model," *IEEE Trans. Electron Devices*, vol. ED-28, pp. 511-517, May 1981.
- [10] M. W. Pospieszalski, "Modeling of noise parameters of MESFET's and MODFET's and their frequency and temperature dependence," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1340-1350, Sept. 1989.
- [11] M. W. Pospieszalski, J. D. Galengo, and W. J. Lakatos, "Broadband, low noise, cryogenically-coolable amplifiers in 1 to 40 GHz range," in *1990 MTT-S Int. Microwave Symp.* (Dallas, TX), May 1990, pp. 1253-1256.