OF-2-12

A 20 GHz FET AMPLIFIER IN AN INTEGRATED FINLINE/MICROSTRIP CONFIGURATION

James Ruxton
BTI, Bolriet
150 Mill St.
P.O. Box 53
Carleton Place, Ont.
Canada K7C 3P3

Ruediger Vahldieck
Dept.of Elect. & Comp.Eng.
University of Victoria
P.O. Box 1700
Victoria, British Columbia
Canada V8W 2Y2

Wolfgang J.R. Hoefer
Lab.for Electromagnetic & Microwaves
Dept.of Electrical Engineering
University of Ottawa
Ottawa, Ontario
Canada K1N 6N5

ABSTRACT

This paper describes the design and fabrication of a 20 GHz FET amplifier which uses an integrated combination of finline and microstrip. A broadband finline-to-microstrip transition is presented. The transition incorporates a novel biasing network to provide unconditional stability. The single-stage amplifier including transitions provides better than 6 dB gain over a 1.25 GHz bandwidth.

INTRODUCTION

In recent years much research has been directed towards designing integrated microwave and millimeter-wave systems using planar transmission media such as microstrip and finline, or a combination of the two. Active components in finline technology employ mostly two-terminal devices. However, three-terminal devices such as Field Effect Transistors (FET's) and High Electron Mobility Transistors (HEMT's) are conquering the lower millimeter-wave range, a region of the frequency spectrum previously dominated by two-terminal devices.

In this paper the design of a quasi-planar 20 GHz FET amplifier using a combination of finline and microstrip is described. However, it could be scaled to millimeter-wave frequencies without losing the advantages inherent in its design.

This amplifier was designed using the transistor (NEC NE67300). Scattering parameters for this device were available from the manufacturer only up to 18 GHz. Since it was desirable to predict its performance above this frequency, a suitable device model was developed, and an unconditionally stable amplifier with a 3-dB bandwidth of 17% and about 6 dB of gain at 20 GHz was designed. It has been realized using a finline-microstrip combination. The design of the finline-to-microstrip transition and the FET mounting structure will be described. Finally the measured performance of the amplifier will be presented.

THE TRANSISTOR MODEL

The FET model used in this design is shown in Fig. 1. It was taken from the SUPER-COMPACT [1] library, and the optimization capabilities of this software were utilized to determine the component values in the transistor model in such a way that the computed S-parameters of the model matched the manufacturer-supplied S-parameters in the 2-18 GHz range. This model was then considered valid for frequencies up to 30 GHz.

After optimization by SUPER-COMPACT the values assigned to the various components of the model were those shown in Table 1.

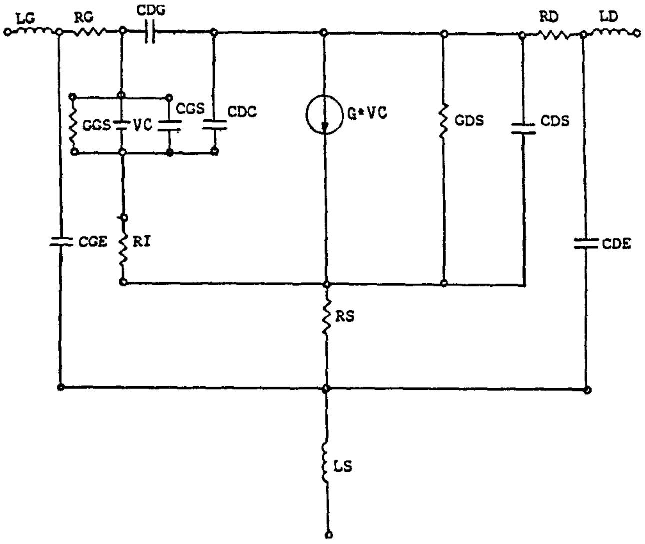

Fig. 1 - FET Model (from SUPER-COMPACT [1] used to simulate the transistor above 18 GHz. The values of the elements are given in Table 1.

Table 1

Component Values in Device Model

G	TRANSCONDUCTANCE	.07
CGS	GATE-SOURCE CAPACITANCE	.32 pF
GGS	GATE-SOURCE CONDUCTANCE	991X10-6
CDG	DRAIN-GATE CAPACITANCE	.03 pF
CDC	DIPOLE LAYER CAPACITANCE	.03 pF
CDS	DRAIN-SOURCE CAPACITANCE	.03 PF
GDS	DRAIN-SOURCE CONDUCTANCE	6.9X10-3
RI	CHANNEL RESISTANCE	10.3 Ohm
RG	GATE RESISTANCE	3.1 Ohm
RD	DRAIN RESISTANCE	3.2 Ohm
RS	SOURCE RESISTANCE	4.2 Ohm
GCE	EXTERNAL GATE CAPACITANCE	.04 pF
CDE	EXTERNAL DRAIN CAPACITANCE	.02 pF
LG	GATE LEAD INDUCTANCE	.03 nH
LD	DRAIN LEAD INDUCTANCE	.03 nH
LS	SOURCE LEAD INDUCTANCE	.01 nH

DESIGN OF THE AMPLIFIER

The amplifier described in this paper was designed as a narrowband high gain device. Very little attempt was made to optimize either bandwidth or noise figure at the expense of gain since the purpose of the study was to develop a circuit configuration in which the transistor itself would provide stable gain. If desired, either the bandwidth or the noise figure of the amplifier could be improved. Since the finline-to-microstrip transition covers almost half a waveguide band, a wideband matching network could be designed to increase the operating bandwidth of the amplifier.

Stability Analysis

Since the impedances of the finline ports become purely reactive below cutoff, care must be taken to ensure that the transistor sees a stable load even in that frequency range. Stability analysis of the FET reveals that the device is potentially unstable at low frequencies for almost any inductive load. The input and output networks must thus be designed such as to avoid the regions of instability at all frequencies.

Matching Network Design

An initial step in the design process was to determine the maximum available gain at 20 GHz, the design frequency. The maximum available gain (MAG) is defined as

$$\mathrm{MAG} = \frac{|S_{21}|}{|S_{12}|}\,(K-\sqrt{K^2-1}) \qquad (1)$$

where K is Rollet's stability factor.

MAG was found to be 6.8 dB at 20 GHz. The load and source terminations which the transistor must see in order to achieve the maximum available gain are, respectively:

$$\Gamma_{MS} = .79 \angle -145$$
$$\Gamma_{ML} = .46 \angle 132$$

These correspond to the following normalized impedances and admittances (reference 50 Ω):

$$Z_{in} = 6.8-j15.3 \qquad Y_{in} = \frac{1}{Z_{in}} = .023+j.055$$

$$Z_{out}=21.5+j18.6 \qquad Y_{out}= \frac{1}{Z_{out}} = .027-j.023$$

Single-shunt stub tuners were used to realize the input and output matching networks The circuit was optimized with TOUCHSTONE over the range 19.5-20.5 GHz to yield optimum gain. The parameters which could vary were the input and output stub length and their distance to the FET. A minimum distance of 15 mils from the FET was enforced for feasibility. The stub lengths and positions were as follows: the input matching stub was 64 mils long and 15 mils from the bond wires; the output stub was 197 mils from the bond wires and 164 mils long. Also, both matching networks included a quarter-wave transformer matching the 50 Ω amplifier terminals to the 121 Ω microstrip used in the microstrip-to-finline transistions, which will be described next.

The Finline-to-Microstrip Transition

With the finline-to-microstrip transition the amplifier can be integrated into a finline environment or, via an exponential taper, connected to waveguide.

Knorr developed a model for a slotline-to-microstrip transition [3]. This model has been modified, and adapted to describe the finline-to-microstrip transition shown in Fig. 2 together with its equivalent circuit. It consists of a finline and a microstrip crossing each other at right angles. The finline is terminated in a short circuit λ/4 from the junction. The microstrip line is terminated in a bandstop filter which, at 20 GHz, appears as an open-circuit at λ/4 from the junction. A quarter-wave transformer matches the 121 Ω microstrip line at the transition to the 50 Ω bias circuit. Z_{of} and Z_{om} are the characteristic impedances of the finline and the microstrip, respectively. The value of the turns ratio n for the transformer is dependant on the fields in the slotline. Knorr defined n as the ratio:

$$n = \frac{V(h)}{V_o} \qquad (2)$$

where V_o is the voltage across the slot and V(h) is the voltage on the microstrip side of the circuit. Based on the slot field, Knorr [3] derived an equation for n as:

$$n = \cos 2\pi \frac{Du}{\lambda_0} - \cot q_0' \sin 2\pi \frac{Du}{\lambda_0} \qquad (3)$$

$$q_0' = \frac{2\pi Du}{\lambda} + \tan^{-1}\frac{u}{v} \qquad (4)$$

$$u = \sqrt{\varepsilon_r - \left(\frac{\lambda}{\lambda'}\right)^2} \qquad (5)$$

$$v = \sqrt{\left(\frac{\lambda}{\lambda'}\right)^2 - 1} \qquad (6)$$

$$\frac{\lambda}{\lambda'} = \sqrt{\varepsilon_{eff}} \qquad (7)$$

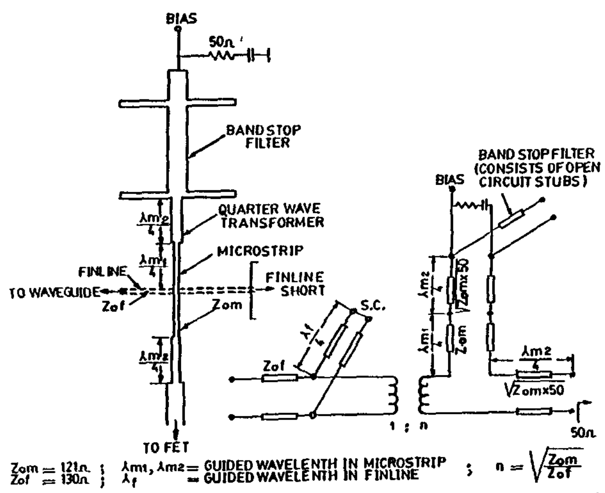

Fig. 2 - Geometry (a) and equivalent circuit (b) of the finline-to-microstrip transition.

In these expressions λ' is the guided wavelength. D is the substrate thickness. A finline of relatively low impedance (130 Ω) was chosen for the transition. It was low enough to match the microstrip assuming a small transformer ratio, yet not too low so the finline gap became too narrow to realize. Also, if the gap becomes too narrow, losses in the finline increase significantly. For a 130 Ω finline within a WR-42 waveguide housing at 20 GHz, the slot width was found to be .15 mm. This configuration yields an ϵ_{eff} of 1.16. These data were generated using a transverse resonance program [4] which is appropriate for analyzing finlines with extremely narrow slots taking the effect of finite metallization thickness into account. Due to the extremely narrow finline gap, the foreshortening effect at the finline short-circuit is negligeable. The microstrip open-circuit stub is realized by placing a 20 GHz band stop filter a half wavelength from the transition junction, as shown in Fig. 4. Two pairs of open 100 Ω quarter wavelength stubs are separated by a half wavelength 50 Ω line. A 50 Ω resistor and a 36 pf capacitor terminate the filter section at the bias pad. The filter has low insertion loss below the cutoff frequency of the finline so that at low frequencies, the FET sees the 50 Ω terminating resistor which represents a stable load at these frequencies. Placed in front of the bandstop filter, within the half-wavelength line, was a 78 Ω quarter wave transformer to transform the 121 Ω microstrip line impedance to the 50 Ω of the bias circuit.

The fins were protected with a thin mylar sheet. The optimum position for the short-circuit is a quarter wavelength (2.8 mm) from the cross-over point of the junction.

The complete transition was analyzed with TOUCHSTONE.

From the theoretical results a relatively broadband transition was anticipated: less than 2 dB insertion loss over more than half the waveguide band. The predicted return loss was better than 25 dB at 20 GHz. To test the transition separately from the amplifier, a back-to-back-transition was fabricated and tested in the amplifier housing. The two transitions were separated by about half an inch of 50 Ω line. Figure 3 shows the measured results obtained in this way, together with the theoretical response. The latter was obtained by neglecting conductor losses in the circuit. However, by assuming an average loss factor of 0.1 dB/wavelength in the transmission line, tapers, and filters, the difference of 1.5 dB between theory and measurement can be accounted for.

PERFORMANCE OF THE COMPLETE AMPLIFIER

Figure 4 shows the layout of the complete amplifier. The transistor mount and the microstrip input and output matching networks are clearly visible in the center. The finline-to-microstrip transitions and the bandstop filters providing stable operation even below finline cutoff are situated at either side. The finline input and output lines are realized on the opposite side of the substrate and, for the purpose of measurement, are tapered into WR-42 waveguide. Note also the rows of plated- through holes along each finline, ensuring complete electromagnetic shielding of the split-block housing across the substrate.

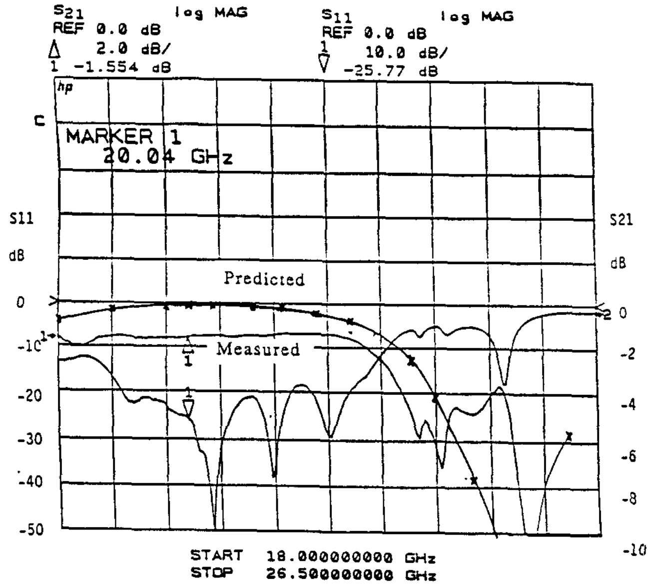

Fig. 3 - Predicted and measured results for two back-to-back finline-to-microstrip transitions.

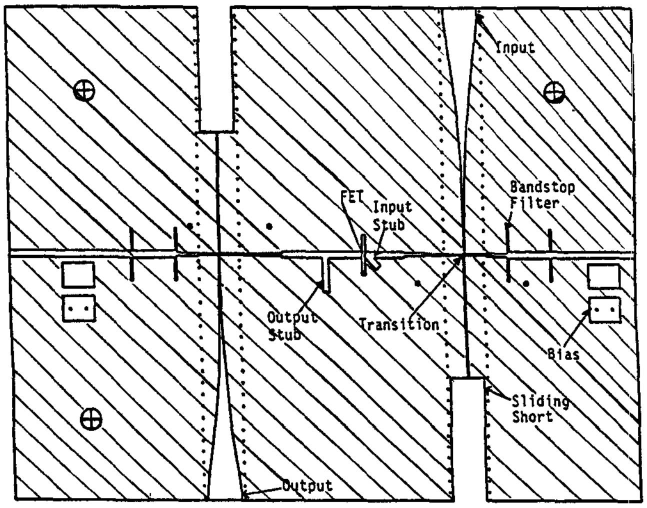

Fig. 4 - Layout of the complete amplifier including transitions and biasing networks.

Figure 5 compares the measured response of the complete amplifier including the finline tapers, with the response predicted with TOUCHSTONE. While the theoretical response was computed using S-parameters for V_{ds} = 3V and I_{ds} = 10 mA, measurements were performed for two bias points (V_{ds} = 3V, I_{ds} = 10 mA, and V_{ds}= 4 V, I_{ds} = 20 mA), the latter measurement showing a maximum gain of 6.7 dB at 20 GHz. The 3 dB bandwidth was 3.4 GHz or 17%.

Figure 6 shows the input and output return losses. Both are better than 10 dB at the center frequency. The input characteristic is slightly shifted to higher frequencies due to the physical constraint imposed upon the input matching stub. The isolation between input and output was better than 17 dB throughout.

Noise performance was not measured. However, the calculated noise figure at 18 GHz was 2.4 dB, and should be only slightly higher at 20 GHz.

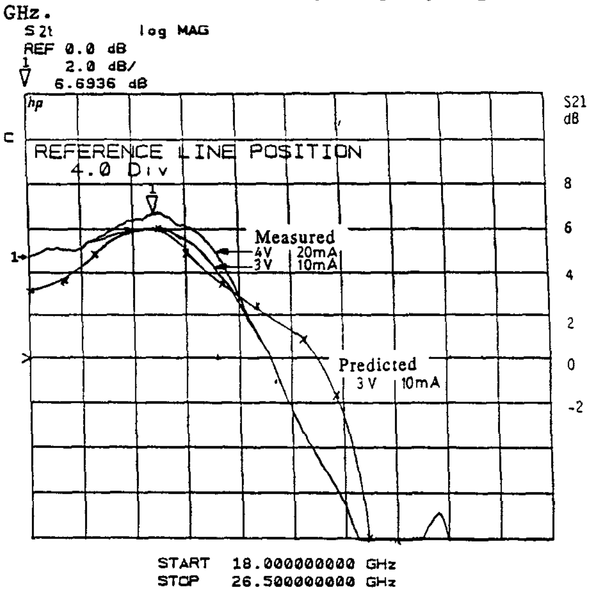

Fig. 5 - Predicted and measured gain of the complete amplifier.

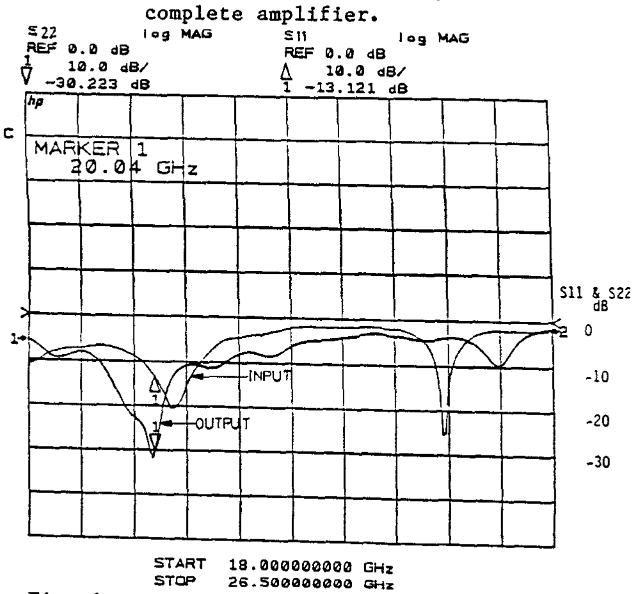

Fig. 6 - Measured input and output return loss of the complete amplifier.

AMPLIFIER FABRICATION TECHNOLOGY

The circuit was fabricated at BTI using a thin-film process. In this process, the copper cladding of the substrate (RT/duroid 5880) is first removed by etching. Then the material is thermally stablized, and a thin film of copper is sputtered onto the bare substrate. The circuit is imaged upon that layer using standard procedures, and etched. The etched circuit is plated to the desired metal thickness, and gold-flashed. Since a very thin layer of copper is being etched, fine lines and spaces as small as 0.001 in. can be realized with this technique. This process is also well suited for the realization of the plated-through holes shown in Fig.4. The amplifier was mounted in a split-block brass housing with milled WR-42 waveguide channels for the finline ports and sliding shorts . The compartments housing the amplifier and the bias networks were accessible for tuning and adjustment purposes.

The amplifier can be reduced considerably in size and weight by replacing the sliding shorts with printed short-circuits, and by manufacturing the housing in metallized plastic, a technique which has been applied successfully in the realization of E-Plane power dividers [5]. The 50 Ω chip resistor in the bias network could also be replaced by depositing thin-film resistors directly onto the substrate. Furthermore, the circuit layout could easily be modified to realize an in-line version in which the RF input and output ports are aligned.

CONCLUSION

The design of a single-stage 20 GHz GaAs FET amplifier in quasi-planar technology has been described. It features a novel combination of finline and microstrip. In particular, a compact, wide-band transition between the finline ports and the microstrip impedance matching networks has been developed and optimized. By virtue of the bias network including a microstrip bandstop filter and a 50 Ω resistor, this transition guarantees unconditonal stability even at frequencies below cutoff of the finline ports.

Good agreement between the measured and calculated results demonstrates the validity of the design process as well as the quality of the fabrication technology. The amplifier can easily be integrated into a finline or a waveguide environment. Alternatively, the transitions may be used in the realization of other components, such as oscillators and filters, requiring finline or waveguide ports.

REFERENCES

[1] Super-Compact version 1.7 (computer program), Compact Software Inc., 483 McLean Blvd. and 18th Ave. Patterson, N.J. 07504.

[2] Touchstone version 1.4 (computer program) EEsof, 31194 La Baya Drive, Westlake Village, CA 91362.

[3] J. Knorr, "Slot Line Transitions", IEEE Trans. Microwave Theory Tech., vol. MTT-22, pp. 548-554, May 1974.

[4] J. Ruxton, W.J.R. Hoefer, "Analysis of Finlines with Extremely Narrow Gapwidths and Thick Metallization", in IEEE MONTECH'-86 Symposium Digest, Monteal, Canada, Sept. 29 to Oct. 1, 1986, pp. 71-73.

[5] J. Ruxton, R. Vahldieck, "A Wideband Finline Power Divider In a Metallized Plastic Housing: Design and Performance in 1987 IEEE MTT Symposium Digest, Las Vegas, June 9 to 11, 1987, pp. 215-218.