AN X-BAND GaAs FET MONOLITHIC POWER AMPLIFIER

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ABSTRACT

Experimental results obtained with a monolithic, one-stage X-band power FET amplifier will be presented along with the CAD design techniques used. Some general considerations relating to the feasibility of GaAs as a monolithic circuit substrate will be given.

Introduction

Semi-insulating GaAs is a low-loss, high permittivity medium eminently suited for microwave integrated circuit applications, such as substrates for microstrip. These properties, combined with the excellent microwave performance of GaAs MESFET's, both as analog devices and as high-speed switches, allows for the first time a truly monolithic approach to microwave integrated circuits. By monolithic, we mean an approach wherein all active and passive circuit elements and interconnections are formed into the bulk, or onto the surface of a GaAs substrate by some deposition scheme, such as epitaxial growth, ion implantation, sputtering, evaporation, and other methods.

The importance of this development is that microwave applications, such as phased array systems based on large numbers of identical elements and requiring small physical volume and/or light weight, may now, finally, become cost-effective.

Maximum cost-effectiveness, as well as maximum reliability and improved circuit performance, require that all wire-bonding within the circuit be eliminated. In this paper we describe a technology for achieving this objective and describe its application to a simple one-stage, narrow-band, X-band monolithic GaAs MESFET power amplifier.

Semi-insulating GaAs, in addition to being a low-loss microstrip medium ($\rho \approx 10^9$ ohm-cm) also is an excellent base for deposition of low-resistivity GaAs layers, such as by epitaxy, which can be used for fabrication of microwave active devices such as FET's.

As a microstrip medium, GaAs exhibits a loss per unit wavelength at X-band slightly higher than alumina and has a somewhat higher dielectric constant, k=12.5. The wavelength of 50-ohm microstrip is approximately 1 cm at 10 GHz. Thus, the feasibility of incorporating matching circuits printed on the same chip as the FET is practical provided the frequency is high enough.

Figure 1 is a plot of the estimated linear dimensions of a microwave integrated circuit on GaAs and the approximate density of these circuits on a 1-inch square wafer area as a function of frequency. The density is an upper limit since it assumes no cutting waste and 100 percent yield. In practice, the realizable density will be closer to 50 percent of the plotted values. It is obvious that incorporating the matching circuit on the GaAs chip is feasible only for C-band and higher.

In this paper we describe the design, fabrication, and evaluation of a series of one-stage X-band FET power amplifiers which incorporate all microwave matching circuitry on the GaAs chip. The only microwave access to the chip are microstrip lines leading to opposite edges of the chip.

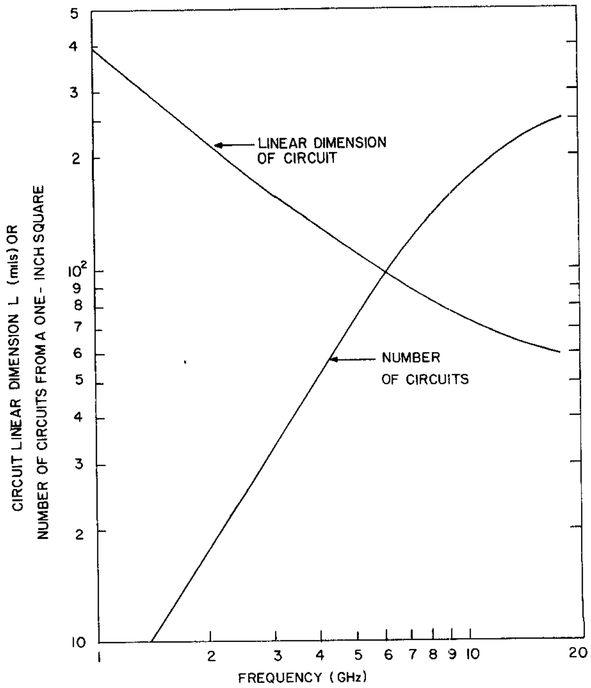

Figure 1. Approximate Linear Dimension of a Monolithic Circuit on GaAs and the Upper Limit on Number of Circuits from a One-Inch Square Wafer as a Function of Operation Frequency Assuming 100 Percent Yield and No Waste

Monolithic Power Amplifier

A single-stage MESFET amplifier was designed to use microstrip circuit elements, and on-chip matching, with the semi-insulating substrate acting as the microstrip propagation medium.

The circuit design was devised using computer-aided-design techniques generally available on commercial time-sharing systems. Two design conditions were tried, one for maximizing the gain at low drive conditions, the other for maximizing the output power at high drive conditions. After preliminary, hand-calculator design, computer optimization techniques were employed to minimize the input and output reflection coefficient or to maximize the gain under high power conditions, as the case may be.

In the spirit of our introduction, the power FET's formed into the active epitaxial layer utilize an air-bridge technology. This technology allows all source electrodes of the individual FET cells comprising the power FET to be interconnected by a metal deposition scheme at the same time as the metal plating for the microstrip circuit elements is deposited. Since the microstrip connections are made to the gate and drain electrodes at the same time, no additional means for connecting the FET to the microstrip circuit, such as wire bonding, is necessary. Hence, a truly monolithic approach is realized.

Figure 2 is a photograph of an X-band amplifier circuit formed in this manner on a 200 by 250 mil chip. This size chip was chosen for ease of testing in a microwave jig and is not indicative of the circuit size reduction achievable by this approach.

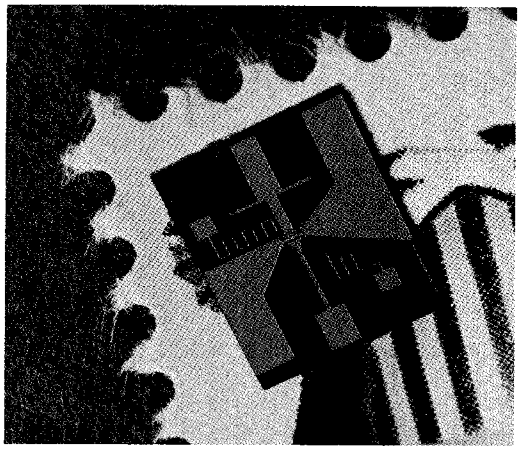

Figure 2. Monolithic X-Band GaAs FET Power Amplifier

The power FET is in the central portion of the chip. The source overlay strap or air-bridge spanning the width of the FET is clearly visible. This strap connects to large-area, low-inductance pads on either side. The size and shape of these pads were chosen to facilitate grounding with metal clamps.

Clearly visible are the microstrip lines and tuning stubs and the meander line gate and drain bias connections. The circuit shown is the one which maximizes the gain. The circuit design for maximum power is similar, but contains stub tuning at both the input (gate) and output (drain) sides.

Figure 3 shows the chip mounted in a special test jig designed for microwave measurements.

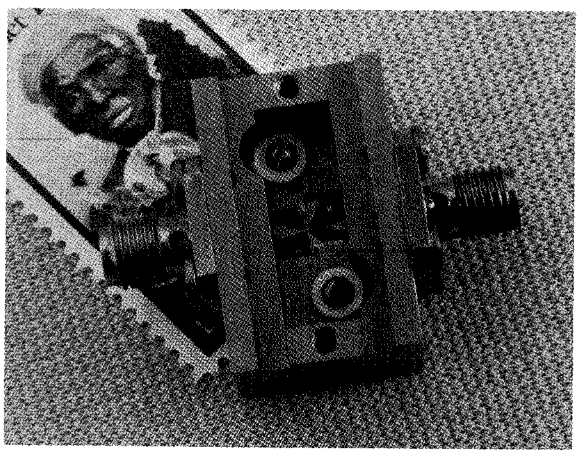

Figure 3. Monolithic Circuit in Microwave Jig

Figure 4 and Figure 5 are computer print-outs of the power gain as a function of frequency for the two designs. It is to be noted that these responses were obtained from the circuits as designed. No "tweaking" or tuning adjustments were made either within the circuit or externally in the microwave "plumbing" connected to the jig. Note the rather respectable bandwidth and gain. No attempts were made in the circuit design to achieve broadband operation, since the experiments were conducted to test the feasibility of the monolithic approach.

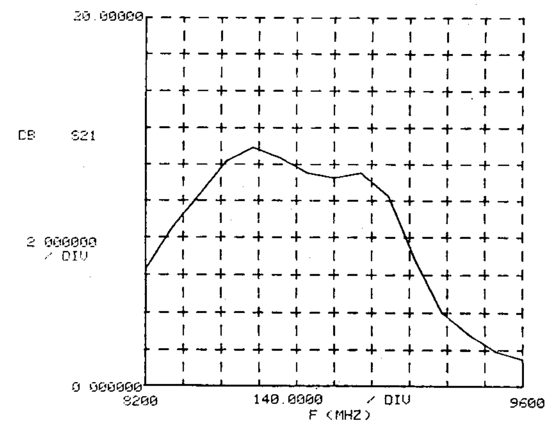

Figure 4. Gain-Frequency Response of Monolithic Amplifier (High-Gain Design)

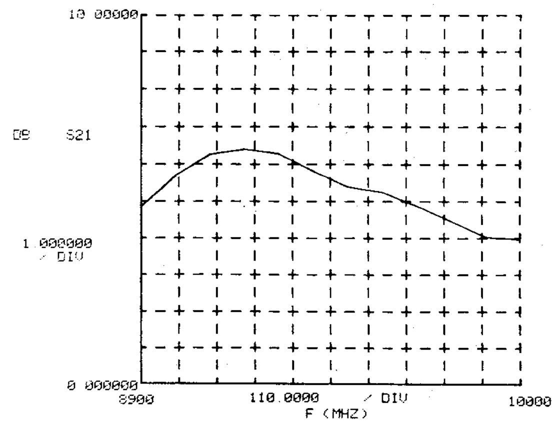

Figure 5. Gain-Frequency Response of Monolithic Amplifier (High-Power Design)

Despite the fact that the S-parameters used in the design were obtained on discrete devices, the center-band frequency was within 5 percent of the design value. The center-band gains were within 2 and 1 dB, respectively, of the predicted values.

Figure 6 is an oscilloscope trace of the power gain as a function of frequency at higher drive levels for the second design. Note the over 400 mW saturated power output at high drive. Figure 7 illustrates the power saturation characteristic measured at center band. The power-added efficiency at saturation was 23 percent.

The large-signal design was based on a load which maximized the power output when the device was biased approximately half-way to pinch-off. This load was determined from the I_d-V_{sg} characteristic. Using this load, and an inductance in shunt to resonate the source-drain capacitance, computer techniques were used to optimize the input circuit for best match. No alteration of the load circuit was made during this optimization.

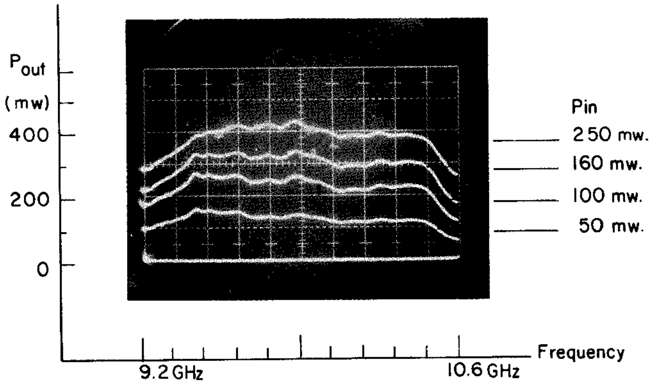

Figure 6. Gain-Frequency Response as a Function of Drive Level (Power Design)

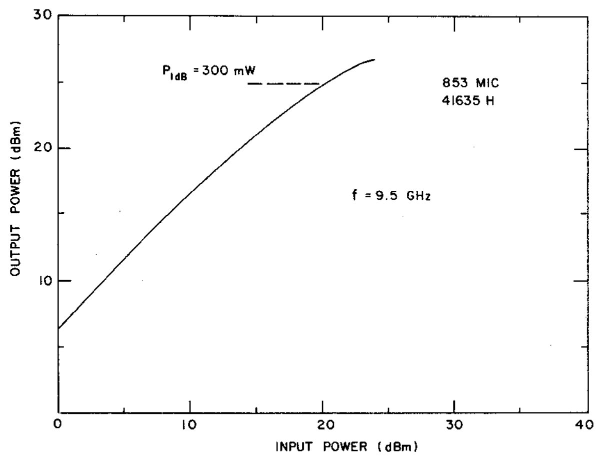

Figure 7. Input-Output Power Characteristic of Monolithic Amplifier

Summary

This paper describes the design principles and techniques and the technology used to achieve a truly monolithic GaAs FET power amplifier at X-band. It was shown that with an air-bridge technology for the FET, an integrated circuit approach using no wire bonds, based on GaAs as a microstrip propagation medium, is feasible for X-band and higher frequencies.

Acknowledgement

This work would not have been possible without the teamwork of the many people, too numerous to mention, who were involved in the completion of this study. We single out, however, R. Mozzi and R. Premo, who were responsible for the fabrication of the device, and Robert Bierig, the manager of the semiconductor device group, at whose suggestion this work was initiated and whose encouragement along the way kept it going at a rapid pace.