Monolithic Millimeter-Wave Pseudomorphic HEMT Power Amplifiers at Ka-Band

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***Abstract*— A Ka-band monolithic HEMT power amplifier, based on 0.25-μm gatelength single quantum-well AlGaAs–InGaAs pseudomorphic high-electron mobility transistor (PM-HEMT) technology, has been developed for millimeter-wave system applications. These amplifiers include single-ended and on-chip combined configurations and have on-chip dc-block, RF-bypass and bias network. A cascaded four-stage power amplifier exhibited 210 mW output power with an associated gain of 21.3 dB at 34.5 GHz. The saturated output power of this amplifier exceeded 230 mW. These power modules need only single positive bias to simplify system power supply requirements, and are highly stable. Moreover, multistages can easily be cascaded/combined to achieved even higher gain and power for future millimeter-wave systems.**

I. Introduction

CONSIDERABLE effort is being directed toward the development of solid-state millimeter-wave components for communications, missile seeker, radar, and radiometry applications. GaAs monolithic millimeter-wave integrated circuits (MMIC's) can potentially reduce cost, enhance performance, and improve reliability of such systems. Recently, MESFET based power MMIC's have been demonstrated for Ka-band system applications [1]–[5], but further gain enhancement is desired which can be achieved using HEMT based power MMIC's. Recently Ferguson *et al.* (7) have achieved excellent performance using HEMT based power MMIC's. However, to achieve such good results, Ferguson et al. used a T-gate process and a double quantum-well device structure. But T-gate fabrication process is somewhat more yield limiting than triangular gate process and single quantum-well structure used by us. In this letter, we describe the design, fabrication, and performance of the 35-GHz pseudomorphic power HEMT MMIC amplifiers using single quantum-well structure that has demonstrated the similar RF results in output power and gain. The design of these power MMIC's makes them very flexible and easy to combine/cascade to achieve high gain and power for system implementation. In addition, the cascaded multistage amplifier is compact, and required only a single positive bias which simplifies system power supply requirements.

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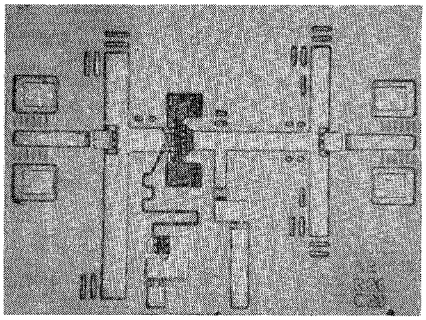
II. Amplifier Design and Fabrication

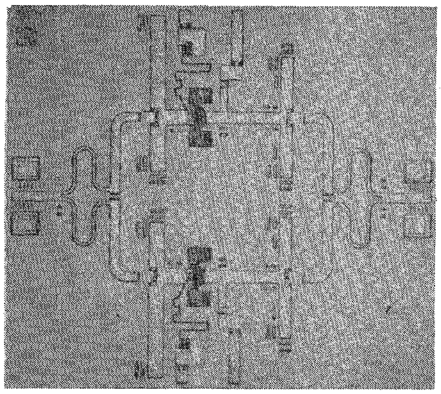
We developed the 35-GHz millimeter-wave monolithic amplifiers using a pseudomorphic HEMT device of 400-μm gate width. The amplifier design consists of an MMIC driver chip driving a MMIC power chip. The baseline monolithic chip design consists of a single-stage, 400-μm PM-HEMT power amplifier with dc-blocking capacitors, on-chip bias, and stabilization networks. To increase the output power capacity, an on-chip Wilkinson power combiner/divider, to be used with two parallel amplifiers, was also designed. The power chip consisted of two driver amplifiers combined in parallel using integrated Wilkinson type divider/combiner circuits. A small-signal equivalent circuit was obtained for the PM-HEMT device by matching an equivalent circuit model to measured S-parameters of a 150-μm device. This model was then scaled to the required 400-μm device model. The optimal load impedance, required by the PM-HEMT device to deliver its maximum power at 35 GHz, was calculated with a load-pull simulation program [5], [6]. Both equivalent circuit model and optimal load impedances were used for driver chip design.

Fig. 1(a) shows the micrograph of the driver MMIC chip. The driver MMIC used open stubs, shorted stubs, and transmission lines as the input and output matching elements. The output matching circuit was designed to present the optimal load impedance to the PM-HEMT in its bandwidth of operation, resulting in maximum delivered power in that bandwidth. The input matching circuit was designed to conjugate match the PM-HEMT input impedance with the device terminated with optimal load impedance to obtain maximum power gain. The source match was then optimized for input return loss and gain flatness across the design bandwidth by using Touchstone microwave circuit analysis program. The stabilization network, consisting of R-C elements, was also incorporated in the MMIC design to ensure the amplifier was electrically stable over a wide bandwidth that extended down to the megahertz region.

The amplifiers were fabricated on epitaxial layers grown by molecular beam epitaxy (MBE) technique. Device structure consisted of only a single quantum-well AlGaAs–InGaAs heterojunction structures. The active areas were isolated by the mesa etching process and a combination of direct-write e-beam and optical lithography was used to fabricate 0.25-μm triangular gates that showed dc gate yields of better than 70 % and fabrication of the circuits. Au–Ge–Ni–Ag–Au alloy and Ti–Pt–Au metallizations were used for the ohmic contacts and



(a)



(b)

Fig. 1. Microphotograph of 35-GHz PM-HEMT power MMIC chip. (a) Driver chip. (b) Combined power chip.

gates, respectively. Si_3N_4 was used for the MIM capacitor dielectric, and for the chip passivation. The chip have via-holes for source grounding. Mesa-resistors in the range of 100 ohms were used as resistive power termination for the on-chip Wilkinson power combiner/divider. The driver MMIC chip size is 1.6 × 1.2 × 0.09 mm. The combined power MMIC chips with input and output power divider/combiner is also shown in Fig. 1(b). The power chip size is 2.7 × 2.4 × 0.09 mm.

III. Measured Performanmce

The MMIC amplifier chips were tested by mounting in a Ka-band amplifier test fixture, which consisted of a copper center block and a pair of low-loss ridged waveguide-to-microstrip transitions [5]. This evaluation approach allowed modules to be cascadable in a multistage amplifier configuration. The single-ended two-stage driver amplifier shows a 14 ± 0.3-dB linear gain for the frequency band of 34 to 35 GHz at maximum power bias. An output power of 100 mW with an associated gain of 11.1 dB was achieved at 34.5 GHz. Saturated output power over 135 mW was also measured at the same frequency. The combined two-stage power amplifier showed a linear gain of 11.2 dB at maximum power bias and an output power of 205 mW with an associated gain of 8.7 dB at 34.5 GHz. The saturated output power of over 230 mW was also achieved at the same frequency. These performances were measured with the MMIC's operating from a single +6 volts dc-bias supply.

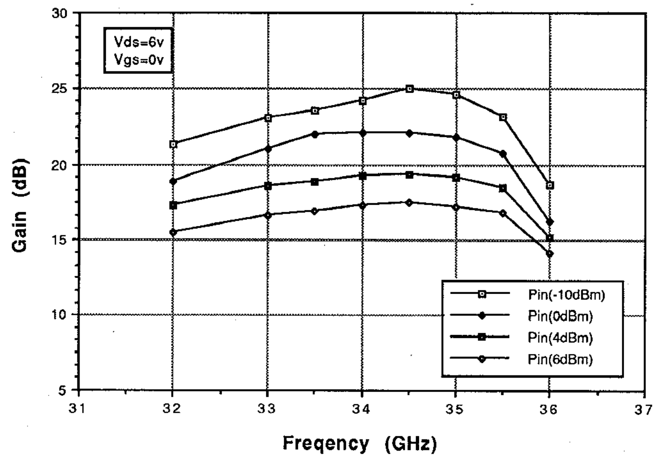


Fig. 2. Measured power gain vs. frequency of four-stage PM-HEMT power amplifier for four input drive levels.

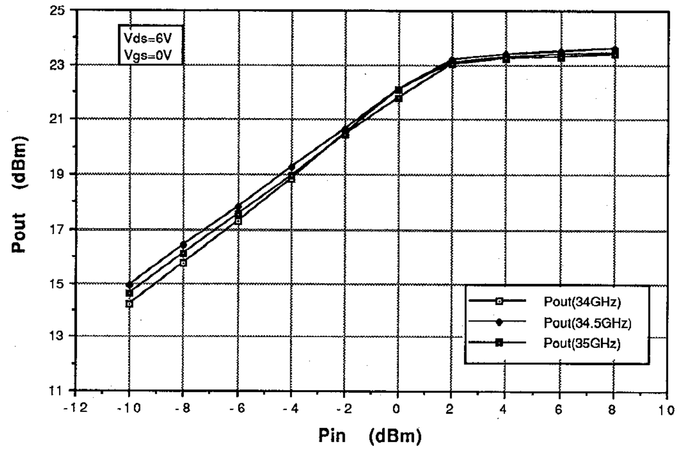


Fig. 3. Measured input power vs. output power of four-stage PM-HEMT power amplifier at 34, 34.5, and 35 GHz.

A four-stage amplifier was assembled by cascading both of the previous two cascaded amplifiers. The first two-stage was a single-ended module and the last two-stage was a combined module with on-chip Wilkinson divider/combiner networks. The associated power gain versus frequency is shown in Fig. 2 for four input drive levels, namely −10, 0, 2, 4, and 6 dBm. This cascaded four-stage amplifier provided a linear gain of 24.8 ± 0.4 dB from the frequency band of 34–35 GHz. The input and output return losses were better than 14 dB and 9 dB, respectively in the same frequency band. Fig. 2 indicates the amplifier also worked well from 33 to 35.5 GHz. The amplifier associated power gain is about 21 dB across the band from 34 to 35 GHz with an output power level of 210 mW. Fig. 3 shows the power transfer characteristics of this amplifier at 34, 34.5 and 35 GHz. It demonstrated a linear gain of 25 dB and an output power of 23.2 dBm (210 mW) with a high associated gain of 21.2 dB at 34.5 GHz. The saturated power of over 230 mW with power added efficiency of 13.2 % was also achieved. This performance of four-stage power amplifier was also measured with each MMIC operating under single +6 volts dc bias. Stable power amplification was obtained with direct cascading of single-ended two-stage and combined two-stage MMIC's.

IV. Conclusion

35-GHz pseudomorphic single quantum-well HEMT power MMIC's have been developed that deliver 210 mW of output power with an associated gain of 21.2 dB. The design of these MMIC chips makes them very flexible and they can easily be combined/cascaded to achieve even higher gains and greater output power using low-loss off-chip power combiner/dividers. Only single positive bias is needed to simplify system power supply operation. These amplifiers are suitable for future millimeter-wave system applications.

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