# Cryogenic Performance of a Monolithic W-Band Amplifier Using Picosecond Optoelectronic Technique

F. Oshita, *Member, IEEE*, M. Martin, *Student Member, IEEE*, M. Matloubian, *Member, IEEE*, H. Fetterman, *Fellow, IEEE*, H. Wang, *Member, IEEE*, K. Tan, *Member, IEEE*, and D. Streit, *Member, IEEE*

***Abstract*—Cryogenic characterization of a monolithic W-band pseudomorphic InGaAs HEMT amplifier has been demonstrated for the first time using the picosecond optoelectronic technique. Low temperature, millimeter-wave measurements have been performed without the use of conventional millimeter-wave sources, components, and transitions. At 94 GHz, the single-stage amplifier exhibits gain of 4.5 dB at 300 K, which increases to 7 dB at 70 K.**

## I. Introduction

THE DEVELOPMENT of InGaAs HEMT technology has made possible the design of high performance monolithic integrated circuits at W-band frequencies [1]–[4]. To date, very little broad-band millimeter-wave measurements have been performed due to cumbersome conventional techniques based on HP8510 network analyzers with frequency extenders or six-port network analyzers. These methods rely on bandwidth limited waveguide components and complex de-embedding procedures to remove the effect of waveguide-to-microstrip transitions. In addition, millimeter-wave on wafer probes are only available up to V-band frequencies [5]. As a result, such limitations have made cryogenic measurements at millimeter-wave frequencies difficult to perform.

As technological advances extend devices and circuits to higher operating frequencies, increasing attention has been focussed on optical techniques based on generation and sampling of picosecond pulses with photoconductive switches to characterize these high speed devices and MMIC's [6]–[8]. In this letter, we report the first broad-band and low-temperature characterization of a W-band monolithic amplifier using the picosecond optoelectronic technique. This method has been successfully applied to obtain $S$-parameters of discrete devices and validated with conventional network analyzer measurements at W-band frequencies [8]. Calibration is simplified with this technique, since there are no transitions to de-embed; only the responsivity of each photoconductive switch is calibrated. In addition, low-temperature measurements are easier to perform, since all electrical information is extracted with low-frequency components. Such low-temperature measurements are important for applications of enhanced performance MMIC's in cryogenic systems.

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F. Oshita, M. Martin, and H. Fetterman are with the Department of Electrical Engineering, University of California, Los Angeles, 64–147 Engineering IV, Los Angeles, CA 90024.

M. Matloubian is with Hughes Research Laboratories, Malibu, CA 90265.

H. Wang, K. Tan, and D. Streit are with the Electronics Technology Division, TRW, Redondo Beach, CA 90278.

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## II. Measurements

Picosecond optoelectronic measurements were performed on a single-stage monolithic W-band amplifier based on pseudomorphic InGaAs HEMT technology. 0.1-um $T$-gate PM HEMT's MBE grown on GaAs substrates have been shown to exhibit excellent noise and gain characteristics at millimeter-wave frequencies [9], and thus, are ideal candidates for high-performance GaAs-based MMIC's. Further details on the device/circuit design and fabrication have been reported elsewhere [2].

The amplifier is mounted between a pair of photoconductive switches in an optoelectronic test fixture [7]. DC bias is provided through SMA connectors and 100 pF off chip capacitors bonded to on chip bias networks. The photoconductive switch material is heavily ion-implanted silicon-on-sapphire. When a picosecond pulse strikes a biased photoconductive gap, a short electrical pulse (FWHM 5 ps) is launched along the center transmission line. A time delayed sampling pulse is used to sample the reflected or transmitted signal. This time domain information is then converted into the frequency domain via Fourier transformation and normalized to yield the wide bandwidth (> 100 GHz) circuit response.

The experimental setup utilizes an actively mode-locked frequency-doubled Nd:YAG laser to pump synchronously a cavity dumped picosecond dye laser that puts out a train of picosecond pulses (600 nm, 70 mW average power, 1.2 ps FWHM). The laser output is divided into a generation and sampling path and focussed onto the appropriate pair of photoconductive switches. The sampling beam passes through a time delay stage that varies the arrival of the sampling pulse relative to the generation pulse. A closed cycle Helium refrigerator has been incorporated into the experimental setup to allow device/circuit characterization at cryogenic temperatures down to 15 K. In this configuration, the circuit under test is kept under ideal vacuum conditions, with the laser pulses coupled through an optical window and the electrical signals extracted through low-frequency SMA feedthroughs.

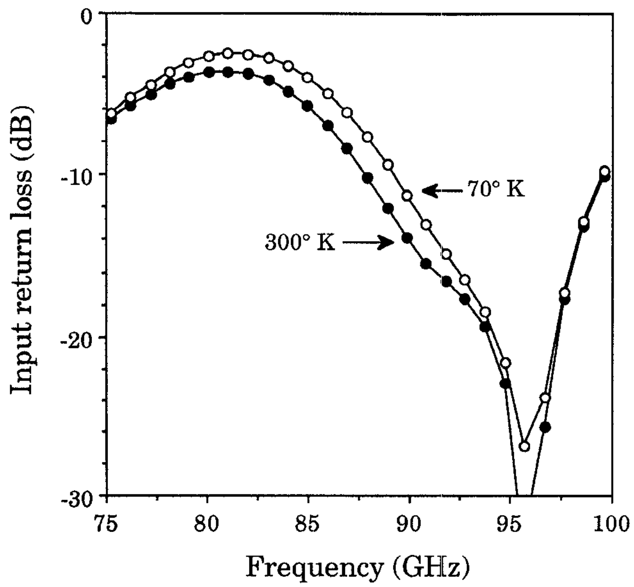


Fig. 1. Measured input return loss of monolithic W-band single-stage amplifier at 300 K and 70 K.

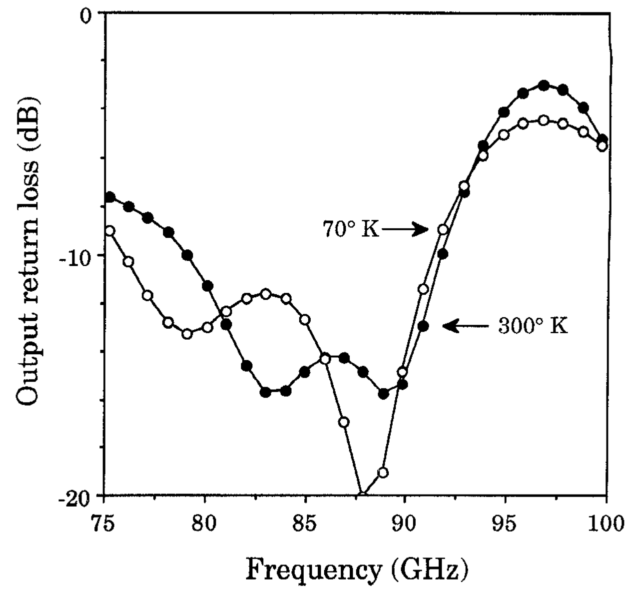


Fig. 2. Measured output return loss of monolithic W-band single-stage amplifier at 300 K and 70 K.

Before circuit measurements are performed, a calibration fixture is prepared with similar photoconductive switches wire bonded together with multiple (5 mil long, 0.7 mil diameter) bond wires. The measured back-to-back insertion loss of this fixture is less than 3 dB with greater than 15-dB return loss from 75 to 100 GHz. When the measurements were repeated at cryogenic temperatures, very little change is observed in the insertion loss; thus, any enhanced circuit performance is expected from the circuit itself rather than the switches or transmission lines. For optimum gain performance, the W-band amplifier is biased at $V_d = 3$ V and $V_g = 0$ V.

## III. Results

The input and output return loss measurements of the amplifier at 300 K and 70 K are shown in Figs. 1 and 2. In the optoelectronic reflection measurements, time windowing has been performed to remove to first order the effect of unwanted reflections such as wirebonds. Waveguide measurements at 94 GHz made on a similar amplifier that was bonded with ribbons between a pair of finline transitions yielded input and output return losses of −11 dB and −6 dB, respectively. These measurements were not de-embedded to remove the effect of transitions and wirebonds, and thus, accounts for the discrepancy with the optoelectronic measurements.

The calibration fixture measurements are used to obtain a first order correction for wirebond loss in the measured gain of the amplifier. This corrected gain at 300 K and 70 K is shown in Fig. 3. At 85 GHz, the single-stage amplifier shows an increase in gain from 9 dB at 300 K to 10.5 dB at 70 K. An overall improvement in gain of 1.5 dB to 2.5 dB over the bandwidth of 75 to 100 GHz is observed when the amplifier is cooled. These results are consistent with cryogenic measurements reported elsewhere on other amplifiers at lower frequencies [10], [11]. Based on the calibration fixture measurements, approximately 2.5 dB loss at 300 K is expected from the wirebonds at 94 GHz.

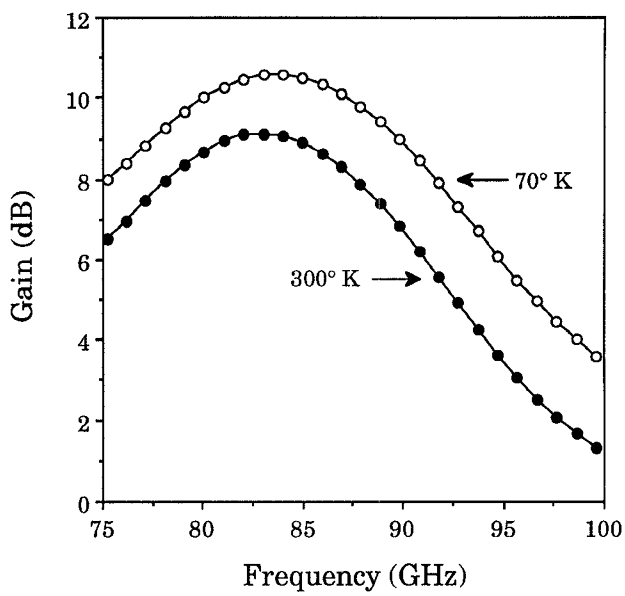


Fig. 3. Measured gain of monolithic W-band single-stage amplifier at 300 K and 70 K. Gain has been corrected for wirebond loss from calibration fixture measurements.

When this is used to compensate the uncorrected amplifier gain data, a room temperature corrected gain of 4.5 dB at 94 GHz is obtained. This is in reasonable agreement with the waveguide measurements, which yielded a corrected gain of 6 dB for a similar amplifier at 94 GHz. Since the repeatability of the optoelectronic measurements has been measured to be within 1 dB, this difference in amplifier gain is likely due to the method used to approximate wirebond loss in the optoelectronic measurements.

## IV. Conclusion

Picosecond optoelectronic measurements have been successfully performed on a pseudomorphic InGaAs HEMT W-band single-stage monolithic amplifier at cryogenic temperatures. The amplifier showed a gain improvement of 1.5–2.5 dB when cooled to 70 K. Work is currently in progress to eliminate the effect of wirebonds in these measurements by monolithically integrating photoconductive switches with MMIC's on the same chip. The experimental setup is also being used to characterize the millimeter-wave and optical responses of pseudomorphic InGaAs HEMT discrete devices at low temperatures.

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