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Experimental investigation of 3-W class-AB cryogenically-cooled amplifier employing GaN HEMT for front end receivers of mobile base stations

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ABSTRACT

This paper presents experimental results of a 2-GHz band gallium nitride high electron mobility transistor (GaN HEMT) amplifier cryogenically-cooled to 60 K as a part of the cryogenic receiver front end (CRFE) for mobile base station receivers. At a temperature of 60 K, the GaN HEMT amplifier attains the maximum power added efficiency of 62%, the saturation output power of 35 dBm, the gain of 26 dB, and the noise figure of 2.6 dB when operating at class-AB biasing. The results reported herein are the first on the performance of a cryogenically-cooled GaN HEMT amplifier aiming at use in a 2-GHz band CRFE.
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1. Introduction

A cryogenic receiver front end (CRFE) comprises a high-temperature superconducting filter (HTSF), a cryogenically-cooled low-noise amplifier (CLNA), and a highly-reliable cryostat [1–3] as shown in Fig. 1. The CRFE is anticipated to be an effective and practical approach to achieve high selectivity and high sensitivity performance for mobile base station receivers since the frequency bands used in mobile radios have become increasingly higher with the growing demand for high-speed and high-capacity data transmission in mobile communications. It is important to attain a high level of selectivity because the frequency bands used by mobile communication system operators should be assigned as closely as possible without interfering with each other. It is also important to attain a high level of sensitivity because the propagation and feeder losses become higher when mobile communication systems use higher frequency bands.

One way to construct the CLNA is to employ a two-stage configuration based on a gallium arsenide high electron mobility transistor (GaAs HEMT) and GaAs field-effect transistor (GaAs FET). The GaAs HEMT is used as the first stage because of its low-noise figure (NF) characteristics, while the GaAs FET is used as the second stage because of its high linearity [2,3]. The second stage amplifier is also required to achieve a high level of power added efficiency (PAE) from the standpoint of mitigating the cryostat cooling capability, which leads to miniaturization of the CRFE. In addition, the second stage amplifier is required to attain a high level of saturation output power e.g., several watts, because non-linear distortion components generated by the second stage amplifier should be negligibly small in order to prevent transmission quality degradation.

The gallium nitride HEMT (GaN HEMT) has drawn much attention recently as a power device in microwave applications due to its high voltage operation and higher power density compared to the GaAs FET [4]. It is known that the GaN HEMT offers high linearity and high PAE characteristics for base station power amplifiers [4]. The GaN HEMT features seem to be effective in further downsizing of the CRFE. However, there are no reports regarding the characteristics of a cryogenically-cooled GaN HEMT amplifier for the CRFE.

This paper presents experimental results of a fabricated cryogenically-cooled amplifier employing the GaN HEMT as the first step toward applying the GaN HEMT to the CRFE. The cryogenically-cooled GaN HEMT amplifier configuration is described in Section 2. The experimental results are presented in Section 3. The conclusion is given in Section 4.

2. GaN HEMT amplifier configuration

2.1. GaN HEMT

This study employs a commercially-available GaN HEMT, which is designed for high-power applications in the L-band. The device has a 3-dB gain compression power of 36.5 dBm, a PAE of 55%, and a linear gain of 19.0 dB at 2.0 GHz. The device uses a metal–ceramic hermetic package and the recommended package operation temperature is 298 K.

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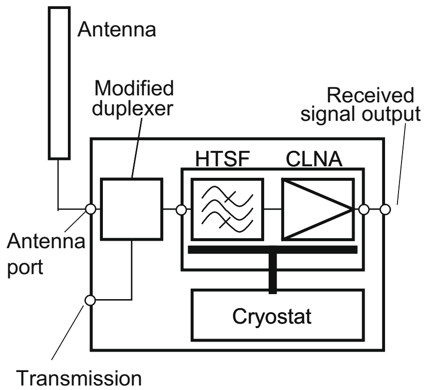

Fig. 1. Example of CRFE configuration for mobile base station receivers.

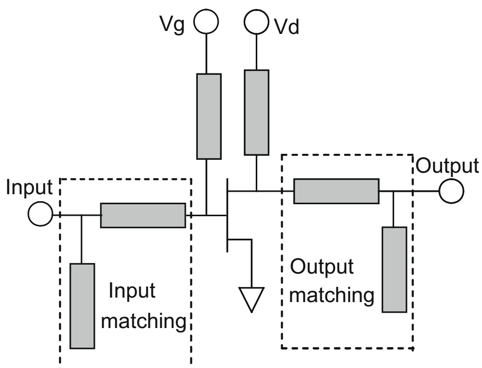

Fig. 2. Circuit schematic of the fabricated amplifier.

2.2. Fabricated amplifier

Figs. 2 and 3 show a schematic and a photograph of the fabricated amplifier employing the GaN HEMT, respectively. The amplifier is fabricated on a substrate with the dielectric constant of 2.15. The substrate is mounted onto a fixture. The fabricated amplifier has two open stubs for input and output matching circuits so that the maximum gain at 2.0 GHz is achieved at 300 K. The fabricated amplifier does not offer the minimum NF because the fabricated amplifier is employed as the second stage amplifier to reduce the power consumption of the CLNA. The drain and gate bias networks

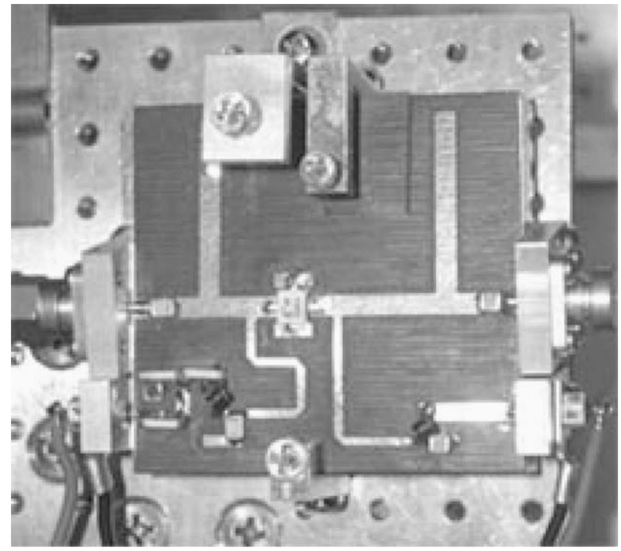

Fig. 3. Photograph of the fabricated amplifier.

comprise a 1/4 wavelength transmission line designed at 2.0 GHz and an electrical magnetic interference filter to avoid parasitic oscillations.

3. Experimental results

3.1. Measurement configuration

In this paper, all measurements are performed without HTSFs. Fig. 4 shows the measurement configuration comprising a vacuum chamber in which the cold stage of a Gifford–McMahon type cryocooler [5] is installed. The cooling power of the cryocooler is 5 W at 20 K. The vacuum chamber has no windows to avoid light exposure. The fabricated amplifier is mounted on the cold stage as the device under test (DUT). The temperature of the cold stage is monitored via the temperature sensor. An indium sheet is inserted between the DUT and the cold stage to ensure sufficient thermal conduction and to minimize the temperature difference between the DUT and the cold stage as much as possible. Since it is difficult to measure accurately and directly the channel temperature of the GaN HEMT, the channel temperature is supposed to be the same as the cold stage based on the above procedure. The cryogenically-

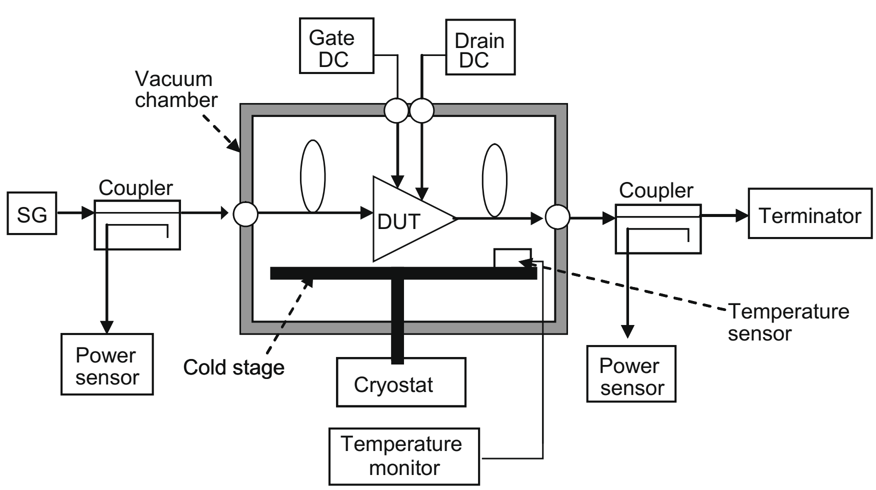

Fig. 4. Measurement configuration for the fabricated amplifier.

cooled experiments are performed at 60 K because the temperature margin must be obtained based on the HTSF critical temperature, e.g., 77 K.

3.2. DC I–V characteristics

Figs. 5 and 6 show the DC current–voltage (I–V) characteristics at 300 K and 60 K, respectively. The DC I–V characteristics are measured without an RF input signal. The drain-source voltage, V_{ds}, is set in decreasing order from 50 V to 5 V. From Figs. 5 and 6, the drain-source current at the gate-source voltage $V_{gs} = -1.17$ V, I_{ds}, at 60 K increases much faster than that at 300 K. The DC I–V characteristics in Fig. 6 seem to exhibit a typical current collapse phenomenon under cryogenic temperature conditions without light illumination as described in [6–9].

Fig. 7 shows the transconductance, g_m, values at 300 K and 60 K that are calculated from Figs. 5 and 6. At the V_{ds} of 50 V, the g_m at 60 K and 300 K are 190 mS and 88 mS, respectively. The maximum g_m at 60 K is 150 mS greater than that at 300 K at the V_{ds} of 30 V. Even in the V_{ds} range from 10 V to 50 V, the g_m at 60 K is greater than that at 300 K, although the DC I–V characteristics at 60 K seem to exhibit the current collapse phenomenon.

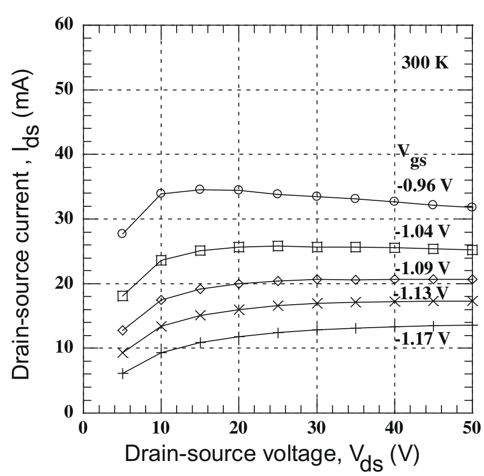

Fig. 5. Drain-source current vs. drain-source voltage measured at 300 K.

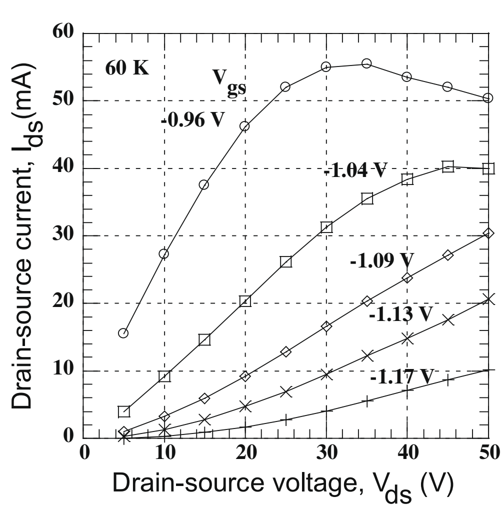

Fig. 6. Drain-source current vs. drain-source voltage measured at 60 K.

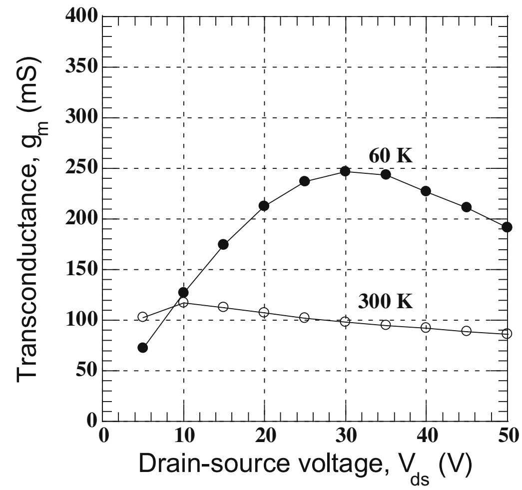

Fig. 7. Transconductance of the fabricated amplifier measured at 60 K and 300 K.

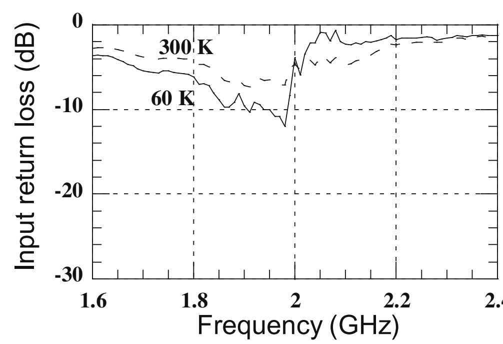

Fig. 8. Input return loss (S11) of the fabricated amplifier measured at 60 K and 300 K.

In this experiment, the bias condition of the fabricated amplifier is based on the recommended operating conditions for the device at 300 K and is set for class-AB operation at both 300 K and 60 K as $I_{ds} = 50$ mA and $V_{ds} = 50$ V.

3.3. S-parameters

Figs. 8 and 9 show the input and output return losses of the fabricated amplifier. At 60 K, the input and output return losses at the input and output ports are less than −3.8 dB and −8.0 dB, respectively. The input return loss at 2.0 GHz and 60 K is not degraded

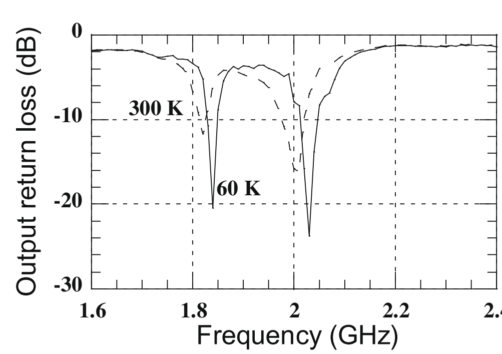

Fig. 9. Output return loss (S22) of the fabricated amplifier measured at 60 K and 300 K.

compared to that at 300 K. On the other hand, the output return loss at 2.0 GHz and 60 K is degraded by 8.0 dB compared to that at 300 K.

3.4. Output power performance

Fig. 10 shows the output power and gain versus the input power characteristics of the fabricated amplifier. The saturation output power at 60 K is about 35 dBm as well as that at 300 K. The gain at 60 K and 300 K are 26 dB and 23 dB at the input power of 0 dBm, respectively. It is known that the gain of HEMT increases due to cryogenic temperature operation [10,11], and the current experiment results support the same findings. The improvement in the gain is approximately 3 dB at 60 K. These results are reasonable because the g_m ratio between 60 K and 300 K is 2.16 (190 mS/88 mS, which corresponds to 3.34 dB) as shown in Fig. 7.

3.5. Power added efficiency performance

Fig. 11 shows the PAE performance of the fabricated amplifier at 60 K and 300 K. The horizontal and the vertical axes indicate the output power and the PAE, respectively. The maximum PAE at 60 K and 300 K are 62% and 57%, respectively. The fabricated amplifier at 60 K achieves a 5% improvement in the PAE compared to that at 300 K. This is because of the improvement in the gain as shown in Fig. 10. These experimental results show that the power consumption of the CLNA is reduced.

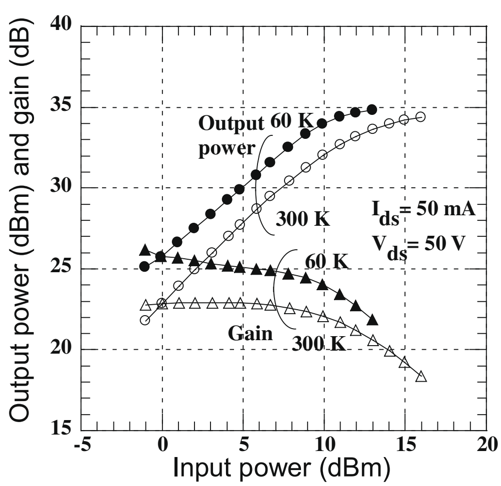

Fig. 10. Output power performance of the fabricated amplifier measured at 60 K and 300 K.

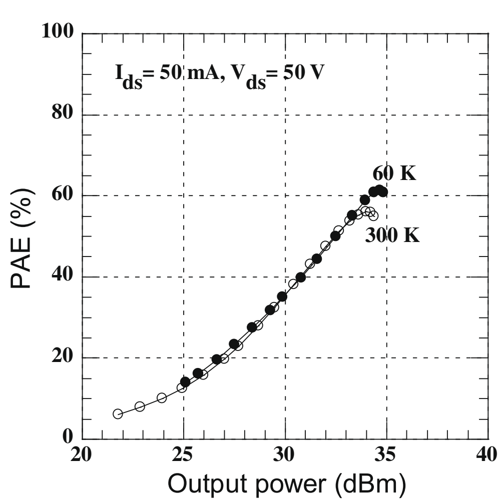

Fig. 11. PAE performance of the fabricated amplifier measured at 60 K and 300 K.

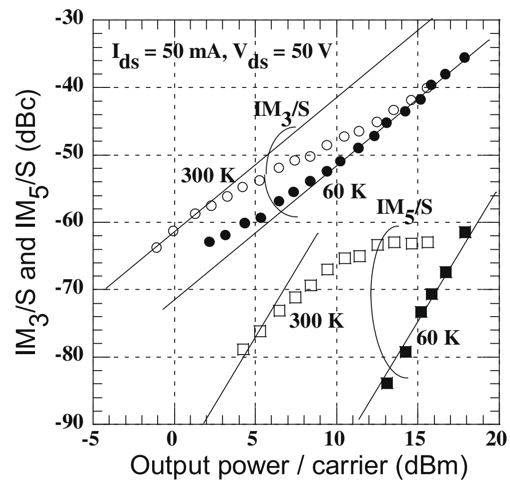

Fig. 12. Third-order and fifth-order intermodulation distortion performance of the fabricated amplifier measured at 60 K and 300 K. Lines approximate the experimental data of IM3/S and IM5/S.

3.6. Intermodulation distortion performance

Fig. 12 shows the third-order and the fifth-order intermodulation distortion (IMD) performance levels of the fabricated amplifier using a two-tone signal at 2 GHz with an offset frequency of 100 kHz. Here, IM_3/S and IM_5/S stand for the ratio of the third-order IMD level to the signal-tone power level and the fifth-order IMD level to the signal-tone power level, respectively. The plots in Fig. 12 indicate the experimental results. The guide lines show slopes of two and four, which only indicate the third-order and fifth-order IMD components, respectively.

IM_3/S and IM_5/S at 60 K are suppressed by more than 4 dB and 20 dB compared to those at 300 K under the output power per tone of 10 dBm, respectively. At 300 K, the experimental results of IM_3/S do not fit the slope of two of the line because the experimental results show that more than 3 dBm of the output power per tone includes higher-order IMD components. For the same reason, the experimental results for IM_5/S do not fit the slope of four of the line, either. The reason for this is because the fabricated amplifier is operated at class-AB biasing.

On the other hand, the experimental results of IM_3/S and IM_5/S at 60 K approximately fit the slopes of two and four of the lines, respectively. The output power difference between the lines of IM_3/S at 300 K and 60 K is 5.0 dB, while the output power difference between the lines of IM_5/S at 300 K and 60 K is 9.5 dB. Based on these experimental results, IM_3/S and IM_5/S at 60 K include negligible higher-order IMD components.

3.7. Noise figure performance

Fig. 13 shows the NF performance of the fabricated amplifier. The NF includes that of the cables inside of the vacuum chamber shown in Fig. 4. The NF meter compensates for the input cable loss of 1.0 dB at 2.0 GHz. The fabricated amplifier offers the NF of 2.6 dB at 60 K and 300 K. There is no improvement in the NF at 60 K, although it is known that for the HEMT an increase in gain as well as a decrease in the NF can be attained by cooling cryogenically [10,11]. The fabricated amplifier is not designed to minimize the

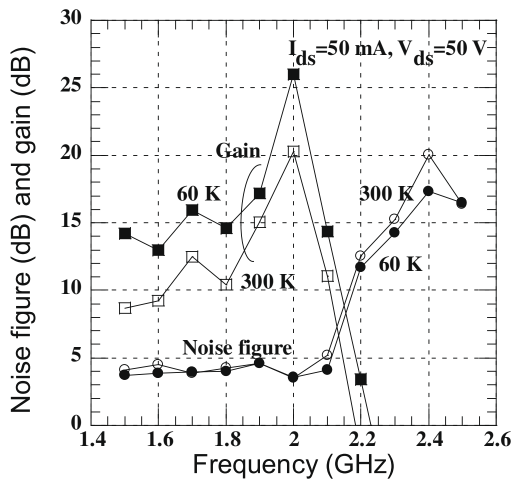

Fig. 13. Noise figure performance of the fabricated amplifier measured at 60 K and 300 K.

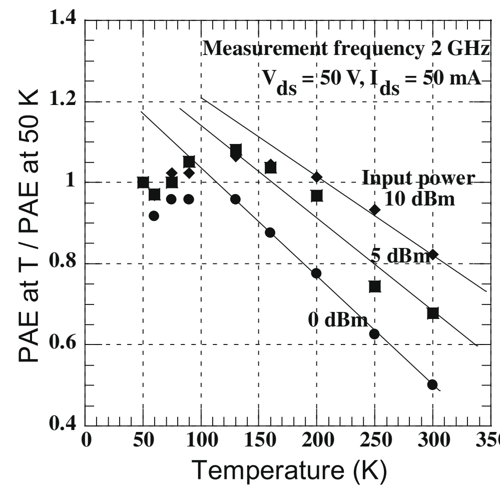

Fig. 15. Temperature dependence of the normalized PAE of the fabricated amplifier. Input powers are 0 dBm (closed circles), 5 dBm (closed squares), and 10 dBm (closed diamonds). Lines approximate the experimental data at greater than 150 K.

NF. The GaN HEMT is not for low NF applications, but for high-power applications. A more detailed investigation is required to evaluate the NF of the GaN HEMT in a cryogenic operating environment.

3.8. Temperature dependencies of RF characteristics

3.8.1. Gain

Fig. 14 shows the temperature dependence of the gain. The horizontal and vertical axes show the normalized gain by the gain at 50 K and the temperature, respectively. The input power is 0 dBm, 5 dBm, and 10 dBm. The experimental results show that for temperatures above 150 K, the normalized gain decreases by 1.0 dB when the temperature increases by 70 K. When lower than 150 K, the normalized gain is saturated in the range from −0.5 dB to +0.5 dB.

3.8.2. Power added efficiency

Fig. 15 shows the temperature dependence of the PAE. The horizontal axis indicates the normalized PAE by the PAE at 50 K. The fabricated amplifier employing the GaN HEMT exhibits a temperature dependence of the PAE when the temperature is greater than 120 K, 150 K, and 200 K at the input power of 0 dBm, 5 dBm, and 10 dBm, respectively. The slope of each input power condition is approximately 0.1/45 K. According to these experimental results, the second stage amplifier employing the GaN HEMT for the CLNA should be cooled to at least 150 K because the temperature dependence is virtually negligible. The required cooling capability of the cryostat for the CLNA can be reduced by improving the PAE of the CLNA. This leads to the miniaturization of the CRFE.

3.9. RF stress test under cryogenically-cooled conditions

Fig. 16 shows the RF stress test under cryogenically-cooled conditions for the fabricated amplifier employing the GaN HEMT. The horizontal and vertical axes indicate the output power deviation and the operation time, respectively. The RF stress test at 60 K employs the 3-dB gain compression point of the output power using a CW at 2.0 GHz as a test signal. The test conditions are the same as those previously reported at room temperature [4]. The deviation in the output power is in the range from −0.2 dB to +0.2 dB during 1000-h of continuous operation. The deviation is almost the same as that in the previously reported test results [4].

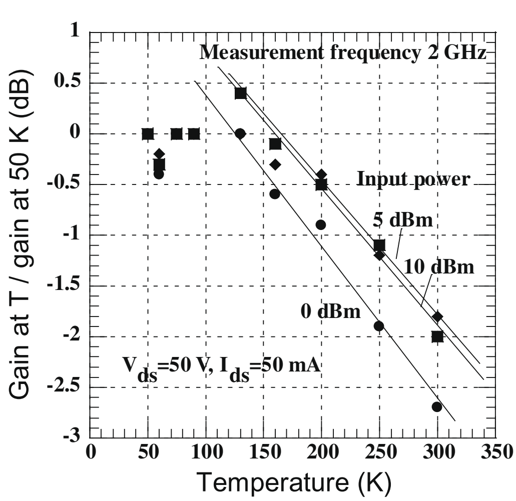

Fig. 14. Temperature dependence of the difference in gain for fabricated amplifier. Input powers are 0 dBm (closed circles), 5 dBm (closed squares), and 10 dBm (closed diamonds). Lines approximate the experimental data at greater than 150 K.

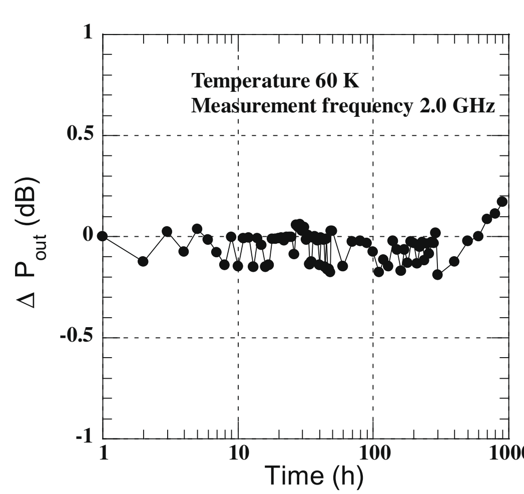

Fig. 16. RF stress testing of the fabricated amplifier at 60 K and 2.0 GHz.

In general, MTTF (mean time to failure) for the HEMT depends on the channel temperature. As far as this experiment is concerned, the GaN HEMT can stably amplify the input signal under cryogenic conditions for about 1000 h. These experimental results exhibit satisfactory performance as the first investigation on the reliability of the GaN HEMT.

4. Conclusion

This paper presented the first investigation of the cryogenically-cooled GaN HEMT amplifier for the cryogenic receiver front end. The fabricated amplifier at 60 K achieved the maximum power added efficiency of 62%, the saturation output power of 35 dBm, and the noise figure of 2.6 dB. The fabricated amplifier at 60 K improved the third-order and fifth-order intermodulation distortion to signal-tone power levels. The experimental results showed that the gain and power added efficiency of the fabricated amplifier decreased when the temperature was higher than 150 K. The fabricated amplifier under cryogenic conditions stably amplified the input signal for about 1000 h with negligible deviations. This paper shows that the GaN HEMT can apply for a cryogenically-cooled amplifier. Our next target is to analyze in detail the non-linearity of the GaN HEMT and to design a two-stage cryogenic LNA using the GaAs HEMT as first stage for the cryogenic receiver front end.

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