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Research Article

The Design and Life Test of a Multifunction Power Amplifier for Space Application

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A new multifunction power amplifier (MFPA) is designed and fabricated for the application of point-to-point K-Band backhaul TR module. A DC temperature life test was performed to model the up-limit temperature effect of the designed MFPA under space application. After 240 hours of 100°C life test, the test results illustrate that the designed MFPA has only slight power degradation at the saturation region without change of the linear gain. The general performance of the designed MFPA satisfies the requirement of the application scenario.

1. Introduction

As one of the most popular III-V binary compound semiconductor devices, GaAs monolithic microwave integrated circuits (MMIC) have attracted many attentions with the advantages of high electron mobility, high cutoff frequency, low noise figure, and good output power and performed superior capabilities for commercial, military, and space applications [1–5]. Regarding the stringent requirements from the market, the most distinct change of GaAs MMIC is the shrinkage of the device size. It brings on high device reliability which becomes a priority for GaAs MMIC device designers. In order to ensure that the reliability of the designed devices fits the proposed application, the Joint Electron Device Engineering Council (JEDEC) was formed, and many standards with respect to semiconductor device fabrication and test were published [6–9] along with other standards for specific applications, such as mil-std-886F. In general, with respect to the application scenario, different test methods are used. The high gate-drain voltage stress used for large signal test is provided to evaluate hot electron effect [10–12]. The test of hydrogen effects which caused the degradation of maximum drain current and surface corrosion is introduced in [13–15].

In this paper, a multifunction power amplifier (MFPA) for the application of point-to-point K-Band backhaul satellite communication is proposed. Due to the space application environment, only the thermal reliability is considered in here at the present stage. The high temperature life test results are reported, under quiescent DC stress with the bias voltages of $V_{DS} = 5\,V$, $V_{GS} = -1\,V$, 100°C of temperature, and 240 hours of time period.

In the following, Section 2 introduces the TR module and MFPA circuit design; Section 3 states the test related setup and test results; following that is the discussion in Section 4; finally, the conclusion is given in Section 5.

2. Circuit Design

The proposed MFPA is used for a point-to-point K-Band backhaul TR module. Each of the designed TR modules includes 4 channels; each channel consists of a vector modulator (VM) for phase and amplitude modulation, a driver amplifier (DRV), an MFPA, a low noise amplifier (LNA), and a CMOS chip used to receive the control signal from the beam forming computer and provide the bias to different chips with respect to the control signal. At the transmission/receiving mode of the MFPA, the RF signal is delivered/collected to/from the left polarized antenna unit at the end of each channel via a driver amplifier (DRV) and

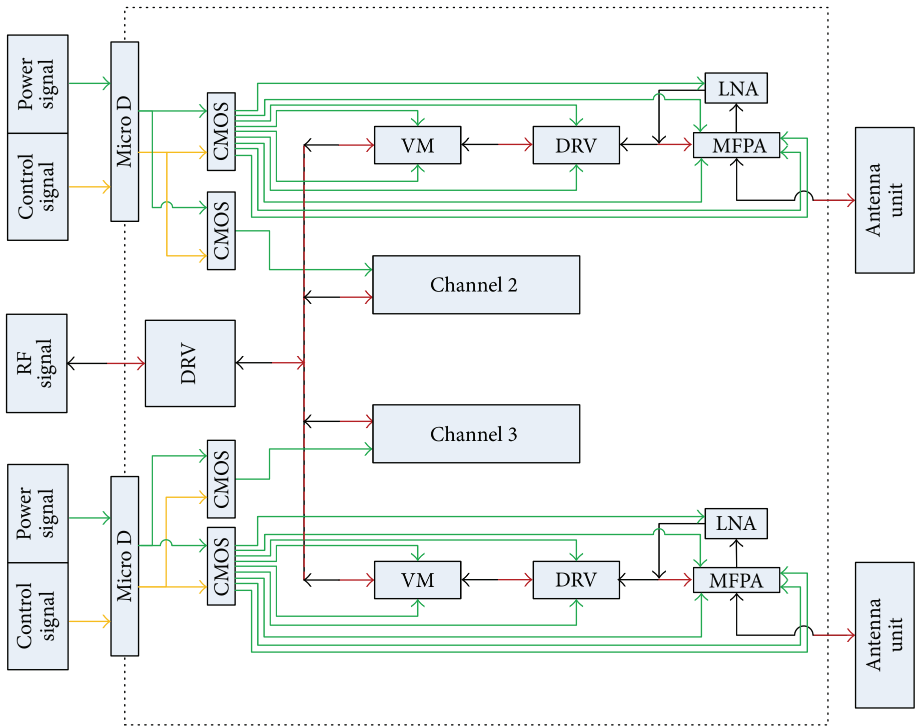

Figure 1: Schematic diagram of the designed TR module hosting the proposed MFPA.

a power splitter/combiner. The schematic design of the TR module is illustrated in Figure 1.

The low temperature cofired ceramic (LTCC) technology is applied to the housing of the TR module [16–18]. It has 16 layers, which are used to cope with different signals and the ground plane. The schematic diagram of the layer distribution is illustrated in Figure 2. As shown, the RF signal is transmitted on layer 12 via a 1 : 4 power splitter (or 4 : 1 power combiner under receive mode). The RF layer is isolated by layers 10, 11, 13, and 14 to prevent the RF interference to DC signal and provide large enough ground for the RF signal. The DC signals are placed on the top, from layer 1 to layer 8. Via holes are used to send the DC signals to the corresponding pads in the RF layer for bias and power supply purpose. The photography of the designed LTCC house cavity is shown in Figure 3.

For the proposed MFPA, it consists of a single pole double throw (SPDT) switch, a transmission channel, and a receiving channel, activating at the transmission mode and the receiving mode of the TR module, respectively. The transmission channel consists of a two-stage amplifier with a $2 \times 40\,\mu$m field effect transistor (FET) as its first stage and a $2 \times 60\,\mu$m FET as its second stage. The receiving channel only consists of a 50 Ω transmission line. The SPDT switch consists of a $2 \times 80\,\mu$m FET and is employed to switch between the transmission and receiving channel. The layout of the designed MFPA is illustrated in Figure 4.

A 0.25 μm GaAs pHEMT technology is used for MFPA fabrication. Typical parameters of the MFPA are measured. The drain current of the MFPA is 360 mA/mm at $V_{GS} = 0$ V and reaches its maximum, 490 mA/mm, at $V_{GS} = 0.5$ V. The channel-on-resistance is 0.94 Ω·mm, and the transconductance is 410 mS/mm. The photograph of the MFPA is shown in Figure 5.

3. Test Setup and Life Test

In order to evaluate the designed MFPA, a three-port test fixture is designed to host the device under test (DUT), shown in Figure 6. In order to retrieve the insertion loss of the DUT and remove the dissipations due to the three microstrip feeding lines and the bonding wires, following test procedures are applied to calibrate the test fixture.

Firstly, the two well-aligned microstrip feed lines connecting port 1 and port 3, respectively, are fabricated by mounting a single microstrip transmission line which connects both ports and removing the middle section of it, whose length is the same as the DUT. Then, one pair of 25 μm gold bonding wires is used to link the two feed lines. After measuring the insertion loss IL_{31} between port 1 and port 3, the bonding wires are removed and another pair of bonding wires is used to link the feed lines connecting port 1 and port 2. Again, the insertion loss IL_{21} between port 1 and port 2 is measured. Finally, the DUT is assembled, and the S-parameters of the test system are measured. The insertion loss of the DUT is then achieved by compensating S21 and S31 with IL_{21} and IL_{31}.

Before performing the life test, the DUT assembled with the test fixture is sealed in a nitrogen environment using a Ni/Au plated Kovar lid and a parallel seam sealer as an individual packaged sample, shown in Figure 7. Then, all the

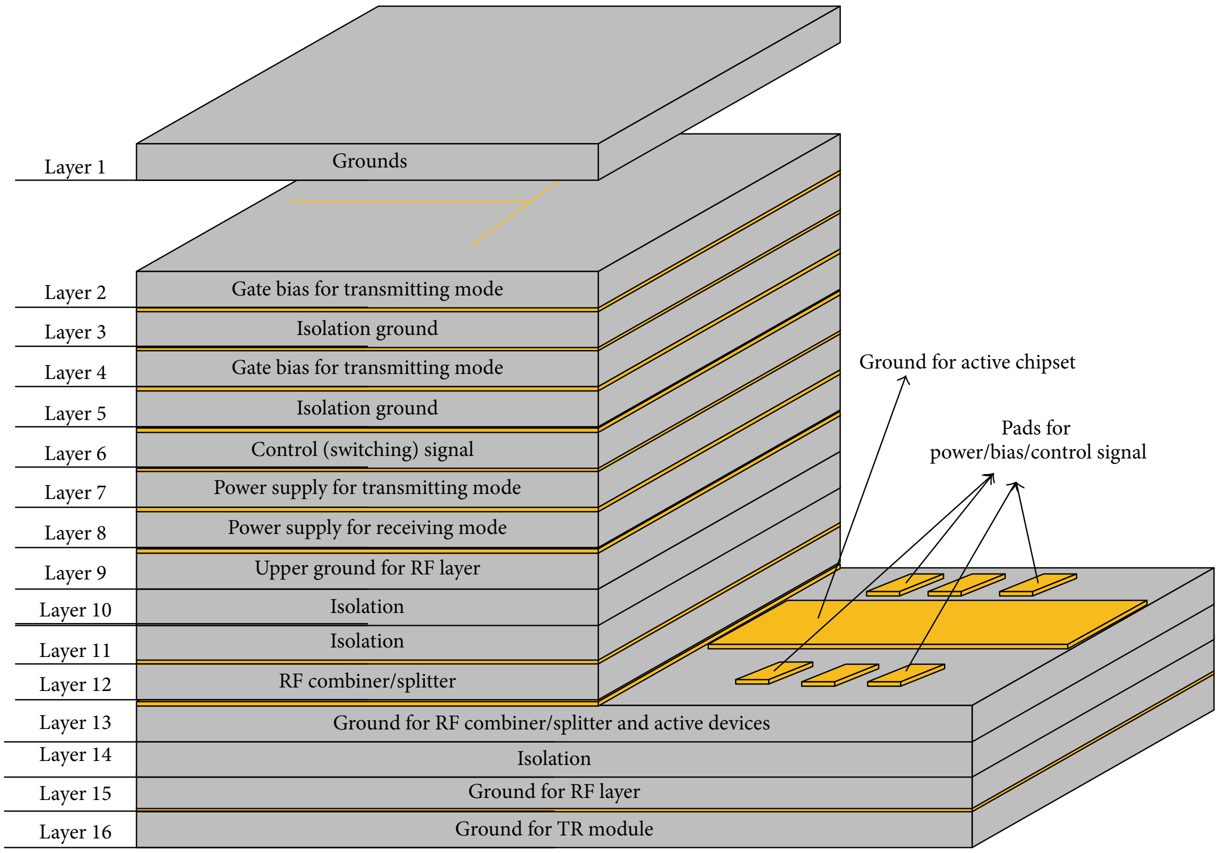

Figure 2: The housing cavity of the MFPA.

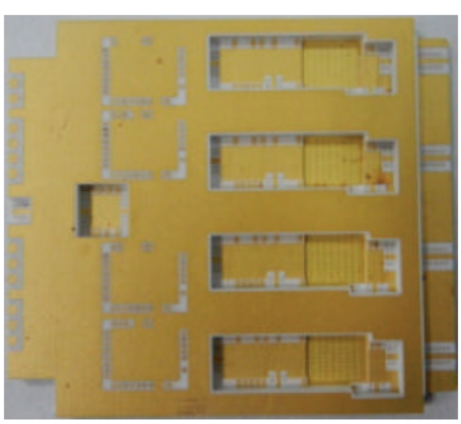

Figure 3: The realization of the LTCC housing cavity.

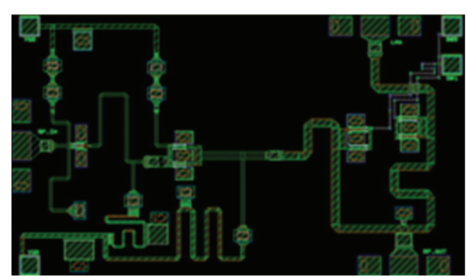

Figure 4: Layout of the proposed MFPA circuit.

packaged samples are fixed onto a mother board as illustrated in Figure 8.

After the packaging, the life test is performed based on a high temperature stress with DC bias. The temperature is set to 100°C and lasts for 240 hours. The same biases as normal operation are set as $V_{DS} = 5$ V and $V_{GS} = -1$ V. The output power and gain against input power before and after the temperature stress are illustrated in Figure 9. When the input power is low, only tiny changes have been observed after 240 hours of temperature stress. As the input power increases, the curves before and after the temperature stress tend to deviate from each other. This deviation reveals the same effect with the one introduced in [19], the saturation gain of which is degraded without change of the linear gain after the RF life test under the condition of 150°C channel temperature, 5 V drain voltage, and 2000-hour test time.

The insertion loss and isolation against frequency before and after temperature stress are illustrated in Figure 10. The isolation and insertion loss are similar before and after the life test. In conclusion, the test results demonstrate that the designed MFPA is insensitive to the life test which means that it is qualified to be used in space applications.

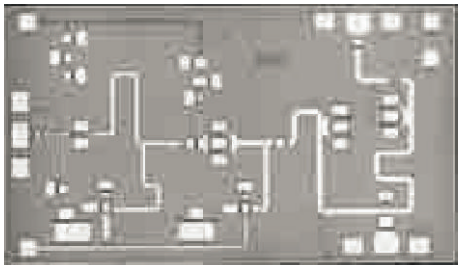

Figure 5: Photo of the fabricated MFPA (chip size: 2.5 mm × 1.4 mm).

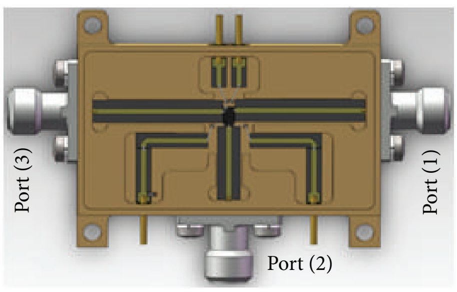

Figure 6: The designed test fixture for the proposed MFPA.

4. Discussion

As illustrated in Figure 9, there is a small degradation at the light saturation (compression region) region. This indicates that the device has some sort of change within the device physically. Such phenomenon could be caused by several GaAs-related degradations such as “hot electron” phenomenon [20–23], metal-semiconductor induced interdiffusion [15, 24], or humidity and hydrogen related degradation [13, 14]. However, in case of hot electron, the holes produced by the impact ionization effects can be trapped in the passivation layer. This leads to the degradation of output power, but according to the authors in [10, 22], the hot electron effect degrades the output power not only in the saturation region but also in the linear region. Therefore, this has ruled out the hot electron to be the major effect that causes the saturation degradation behavior shown in Figure 9.

In case of metal-semiconductor induced interdiffusion, it mainly occurs when the device is under high temperature. Such interdiffusion phenomenon changes the surface state between the metal-semiconductor interface and the buffer layer above the channel layer. It further leads to the change of the barrier height of the metal-semiconductor junction, the channel carrier density, and gate resistivity. All these effects act as the degradation of the drain current and output power. At the linear region, due to the effective number of carriers participating in the drain, current is less than the overall number of the carriers. Therefore, this metal-semiconductor interdiffusion has much less effect on the effective carrier density, which is the reason that the linear region is unchanged after the stress.

With respect to humidity and hydrogen related degradation, the main signatures are the reduction of drain current,

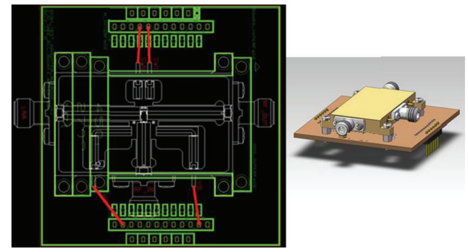

Figure 7: The illustration of packaged DUT.

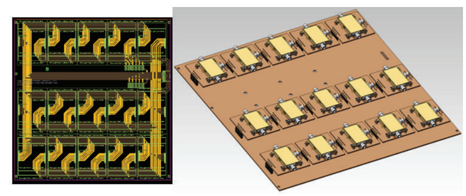

Figure 8: The mother board of the packaged DUT.

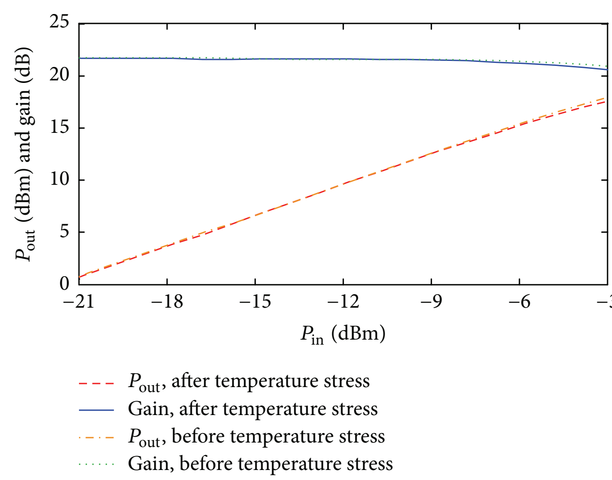

Figure 9: The output power and gain against input power before (blue color traces) and after (red color traces) temperature stress under transmission mode.

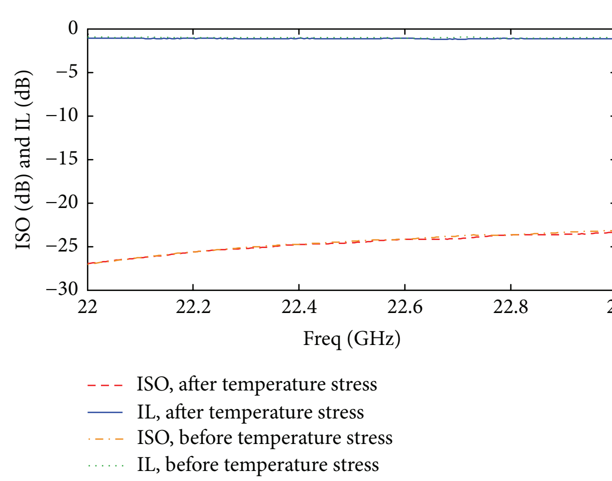

Figure 10: The insertion loss and isolation against frequency before (blue color traces) and after (red color traces) temperature stress.

which leads to the reduction of output power, especially when the DUT is stressed with high temperature condition combined with humidity and hydrogen effects [25, 26]. The possibility of humidity and hydrogen within the hermetic package could cause the adhesion phenomenon with respect to the passivation layer and the damage of the surface state of the semiconductor layer. For the case of our packaging, the sealing process and the housing cavity are checked to avoid the humidity and hydrogen related effects. However, there is no guarantee or evidence to support the absence of such degradation during this life test. More experiments used by the authors in [19] can be used in the near future to estimate the resistivity of humidity and hydrogen related degradation effect for the designed MFPA. Furthermore, the humidity and hydrogen occur on the ground when the device module is prepared. Therefore, the techniques for reducing such effects are highly depending on the module sealing techniques and the components designed techniques. In case of humidity, the following method can be applied to minimize the effects of humidity: (1) Preheating is the most used method to reduce the possibility of humidity for the components and the module cavity. (2) Sealing environmental control is another efficient way of controlling the humidity condition by using temperature control and protection gas. (3) Sealing finishing is to take care of all the interconnections between all the pins and the module cavity and ensure that there is no leakage. For hydrogen effect, the following techniques can be employed to reduce the effect: (1) sealing material selection, to choose the material which has a low hydrogen absorption concentration such as Al; (2) components process technique, to improve the hydrogen resistance by using carefully designed process technique such as using Al as the gate material for GaAs chip; (3) module cavity structure, to optimize the design of the structure in order to let the hydrogen flow within the cavity (this is due to the fact that the flowing hydrogen will have no harm to the components); (4) using of hydrogen absorber, to reduce the hydrogen level under the safe level by placing hydrogen absorber material within the module cavity [15, 27, 28].

In summary, the observed degradation of the output power at saturation region is possibly caused by the metal-semiconductor interdiffusion and/or the humidity and hydrogen related degradation. The true nature of this phenomenon can be further revealed with more tests such as longer temperature life test and thermal shock. The observation techniques such as transmission electron microscopy (TEM) can be used to analyze the change of the pHEMT unit of the designed MFPA with respect to the test conditions and the changing of electrical characteristic, in order to find the relations between the stress condition, the changing of physical, and electrical characteristics of the designed MFPA fully.

5. Conclusion

This paper introduced the design and life test of a K-band MFPA for the application of point-to-point K-Band backhaul TR module. The design of the TR module using LTCC technology and the MFPA using 0.25 μm GaAs MMIC process is provided. After the 240 hours of life test, only slight degradation at saturation region was observed. This indicated that the designed MFPA are suitable for the proposed spatial application scenario. The possible reasons of the degradation phenomenon were discussed in detail. Future work with additional test methods, such as temperature cycling, thermal shocking, and long life test (over 1000 hours), will be performed to further evaluate the designed MFPA.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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