# MMIC Development for Millimeter-Wave Space Application

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***Abstract*—The latest millimeter-wave monolithic-microwave integrated-circuit (MMIC) developments and technologies at the Mitsubishi Electric Corporation, Kanagawa, Japan, concerning high power amplifiers, low-noise amplifiers and phase shifters have been summarized. It has been shown that high-efficiency, low-noise, and low-loss performance for millimeter-wave space applications can be achieved by employing pseudomorphic high electron-mobility transistor (p-HEMT) MMIC technology. The investigation for gamma-ray irradiation hardness has cleared that millimeter wave p-HEMT MMICs have over a 100 years of life against gamma-ray irradiation in the space environment.**

***Index Terms*—Gamma ray, millimeter wave, MMIC, module, p-HEMT, space application.**

## I. Introduction

Monolithic-microwave integrated-circuit (MMIC) technology has been widely used for space applications since the technology is suitable for transponders or sensors, which need high performance, small size, light weight, and high reliability. Especially for on-board active phased-array antenna (APAA) transmitter/receiver (T/R) modules, MMICs will be the best candidates to achieve high reproducibility and performance uniformity.

Fig. 1 shows a block diagram of an on-board APAA system, which includes a number of sub arrays. Each sub array consists of a lot of T/R modules including high power amplifiers (HPAs)/low-noise amplifiers (LNAs), phase shifters (PSs), linearizers (LNZs), and so on. A variable delay line (VDL) is installed at each sub array to achieve good true-time-delay performance for a large-aperture APAA.

We have developed the pseudomorphic high electron-mobility transistor (p-HEMT) MMIC family for millimeter-wave space applications. This paper summarizes our latest millimeter-wave p-HEMT MMIC developments and technologies concerned with HPAs, LNAs, and PSs. They have achieved good performance of high-efficiency, low-noise, and low-loss characteristics for millimeter-wave space applications. From the investigation for gamma-ray irradiation hardness, it has been cleared that millimeter-wave p-HEMT MMICs have over a 100 years of life against gamma-ray irradiation in the space environment.

As a result, it has been shown that p-HEMT MMIC technology is the solution for millimeter-wave space applications.

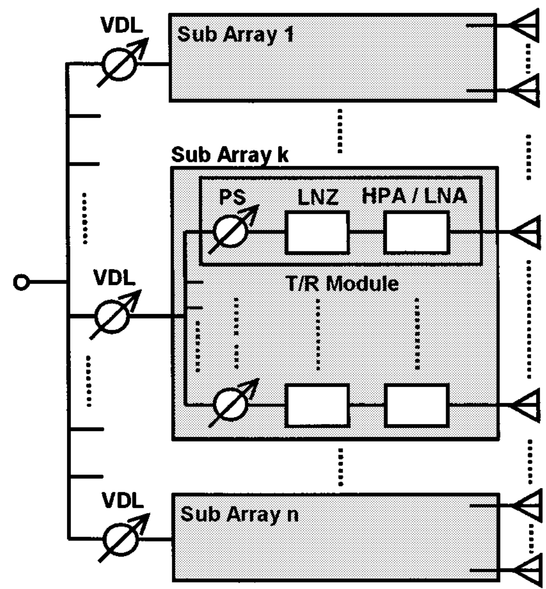


Fig. 1. Block diagram of on-board APAA system.

## II. p-HEMT Device

The p-HEMT device is very useful to achieve high-gain, high-efficiency, and low-noise performance for T/R modules. Fig. 2(a) and (b) shows device structures of a high-power p-HEMT and low noise p-HEMT, respectively. The high-power p-HEMT employs a double heterojunction of AlGaAs/InGaAs/AlGaAs and a T-shaped Al gate process with a gate length of 0.2 $\mu$m. The measured power performance of the high-power p-HEMT with a gatewidth of 600 $\mu$m has a 1-dB gain compress output power of 24.4 dBm with a power-added efficiency of 57% at 18 GHz [1]. The low-noise p-HEMT employs a AlGaAs/InGaAs/GaAs single heterojunction and T-shaped Al gate process with a gate length of 0.15 $\mu$m. The measured noise performance has a minimum noise figure of 0.9 dB with an associated gain of 8 dB at 35 GHz [2].

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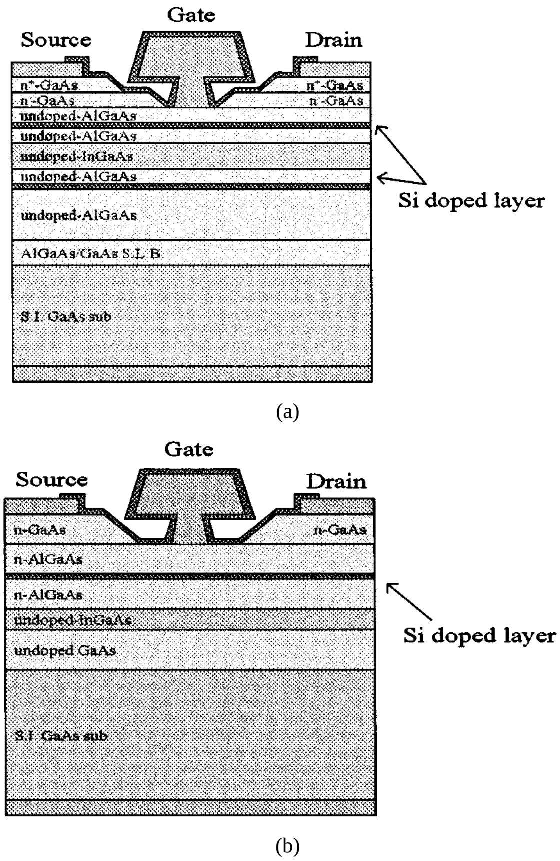



Fig. 2. Device structures of: (a) high-power p-HEMT and (b) low-noise p-HEMT.

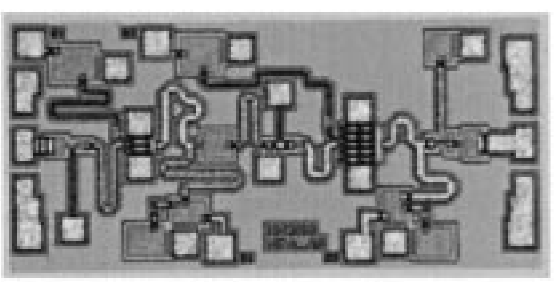


Fig. 3. $K$-band two-stage middle power-amplifier MMIC.

## III. HPA MMICs FOR TRANSMITTER

The p-HEMT technology has been applied to middle power MMIC amplifiers for $K$-band on-board APAA T/R modules. Fig. 3 shows a $K$-band two-stage middle power-amplifier MMIC. It utilizes AlGaAs/InGaAs/GaAs double-heterojunction p-HEMTs as active devices. Since miniaturization of chip size is important to reduce the module size and chip cost, lumped elements are employed at input and inter-stage matching circuits. Fig. 4 shows the measured frequency characteristics of output power and power-added efficiency of the amplifier MMIC. It has delivered the efficiency of more than 30% with an output power of more than 24 dBm over the frequency range from 18 to 19.75 GHz. Fig. 5 shows the measured power performance as a function of a drain bias current for the amplifier MMIC at 19 GHz. The amplifier has achieved a power-added efficiency of 50% with an output power of 24.6 dBm at 19 GHz [1]. Fig. 6 shows the state-of-the-art of efficiency versus output power characteristics for $K$-band multistage p-HEMT amplifier MMICs [3]–[7]. From Fig. 6, it is shown that this amplifier MMIC has demonstrated the state-of-the-art of high efficiency.

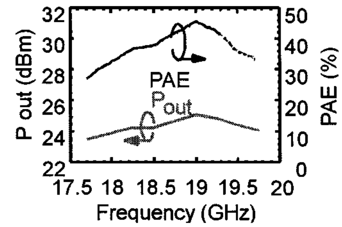



Fig. 4. Measured frequency characteristics of output power and power-added efficiency of the amplifier MMIC.

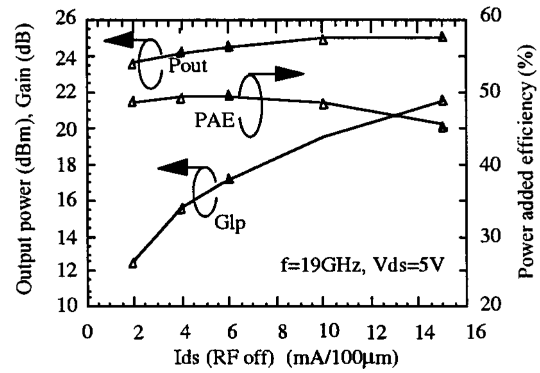



Fig. 5. Measured power performance as a function of a drain bias current for the amplifier MMIC at 19 GHz.

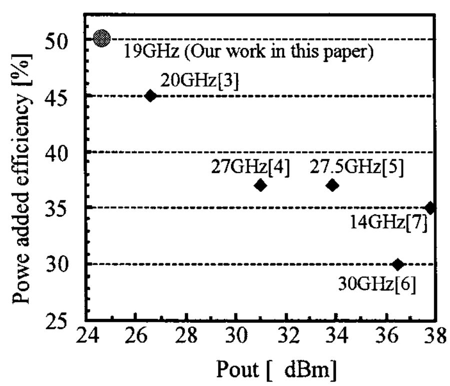



Fig. 6. State-of-the-art of efficiency versus output power characteristics for $K$-band multistage p-HEMT amplifier MMICs.

Fig. 7 shows a $K$-band amplifier module, which includes three MMIC chips. The MMICs are mounted in a low-temperature co-fired ceramic (LTCC) multilayered miniaturized package. The module has delivered an output power of 25 dBm with a gain of 35 dB at $K$-band.

There are increasing demands for high data-rate digital communications such as Internet or multimedia communication systems, where low-distortion and high-efficiency power amplifiers are required. We have developed a novel LNZ MMIC to achieve low-distortion power amplifiers. Fig. 8(a) and (b) shows a photograph of an LNZ MMIC and its schematic diagram, respectively. Fig. 9 shows the measured third-order intermodulation distortion (IMD3) of a power amplifier with and without the

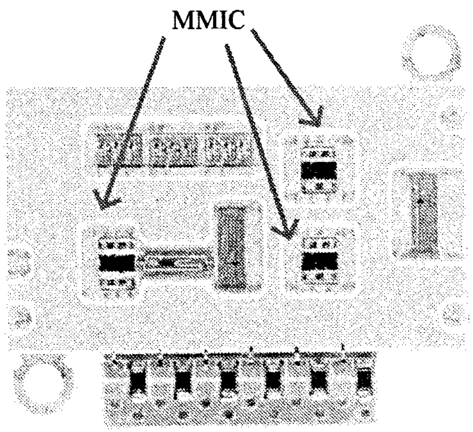
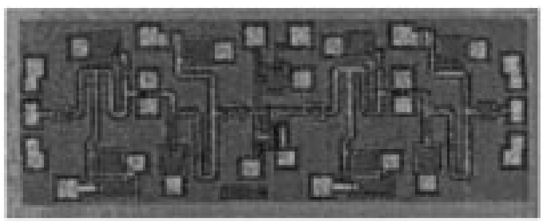
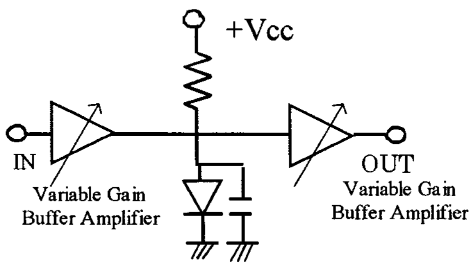



Fig. 7. $K$-band amplifier module mounted in an LTCC multilayered package.



(a)




(b)

Fig. 8. (a) $K$-band LNZ MMIC. (b) Its schematic diagram.

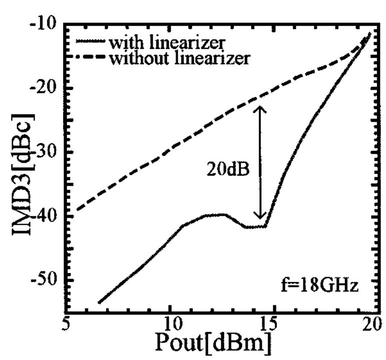



Fig. 9. Measured IMD3 of a power amplifier with and without the LNZ.

LNZ at 18 GHz. An improvement of IMD3 of 20 dB is achieved by using the LNZ [8].

## IV. LNA MMICs for Receiver

An AlGaAs/InGaAs/GaAs single doped p-HEMT with a gate length of 0.15 $\mu$m is employed in LNAs for our space application. We have developed a $K$-band three-stage LNA MMIC for on-board APAA receiver modules. Fig. 10 shows the amplifier

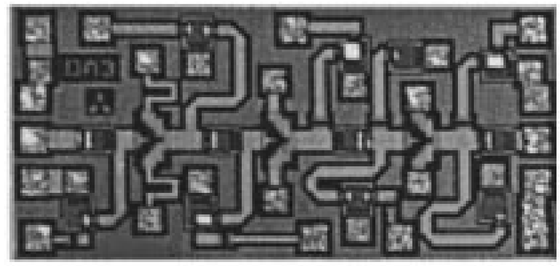


Fig. 10. $K$-band three-stage LNA MMIC.

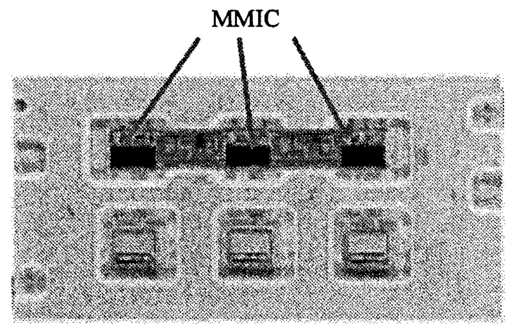
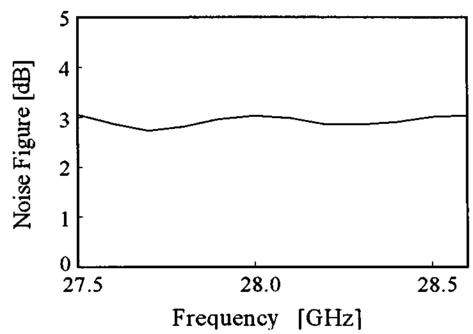
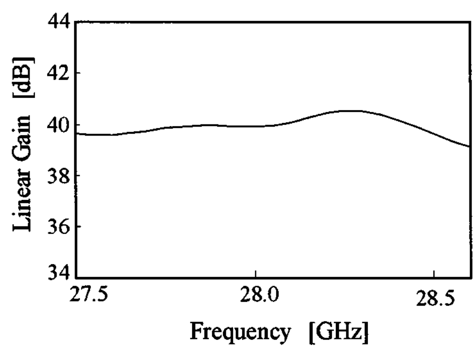



Fig. 11. $K$-band LNA module mounted in an LTCC multilayered package.




(a)




(b)

Fig. 12. Frequency characteristics of: (a) noise figure and (b) linear gain of the module.

MMIC. To achieve low noise figure, high gain, and small reflections simultaneously, a design method is developed to use source inductors having a different value for each stage. As a result, the amplifier has achieved a noise figure of 1.7 dB, a gain of 20 dB, and an input and output return loss of 15 dB at 28 GHz [9]. Fig. 11 shows a $K$-band LNA module, where three chips of the preceding amplifier MMICs are mounted in an LTCC multilayered package. Fig. 12(a) and (b) shows frequency character-

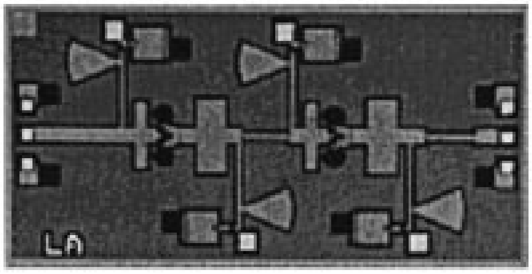



Fig. 13. $W$-band two-stage LNA MMIC.

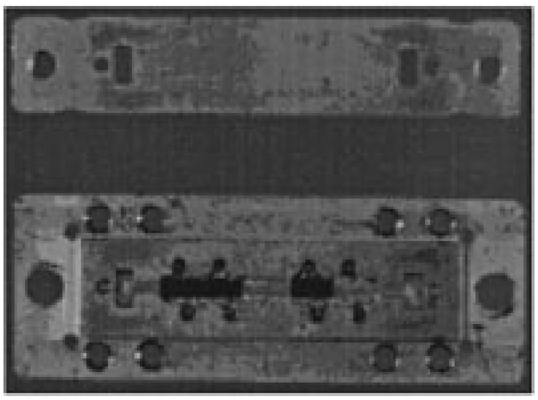


Fig. 14. $W$-band LNA module.

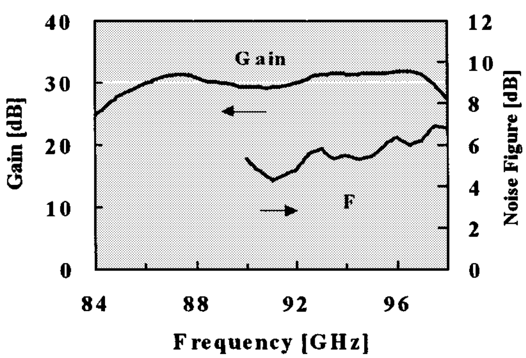



Fig. 15. Frequency characteristics of the noise figure and gain of the amplifier module.

istics of noise figure and gain of the $K$-band amplifier module, respectively. The module achieved a noise figure of 3 dB with a gain of 40 dB at a 28-GHz band [10].

ard radiometric sensors for observation of Earth environments including sea surface temperature, sea ice distribution, etc. For amplifiers used in the sensors, an extremely low noise figure is required to enhance the resolution of the instrument. Fig. 13 shows a $W$-band two-stage LNA MMIC. The measured noise figure of the amplifier is 3.4 dB with gain of 8.7 dB at 91 GHz. Highly reliable and low-loss packages are desirable for millimeter-wave on-board amplifiers. We have developed a hermetically sealed millimeter-wave package with a low-loss waveguide interface. Fig. 14 shows a $W$-band LNA module mounted in the preceding package. Fig. 15 shows frequency characteristics of the noise figure and gain of the amplifier module. The measured result is a noise figure of 4.3 dB with

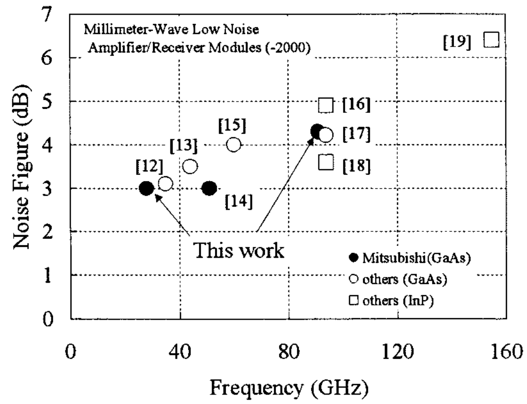



Fig. 16. State-of-the-art of noise-figure characteristics for millimeter-wave multistage amplifier/receiver modules.

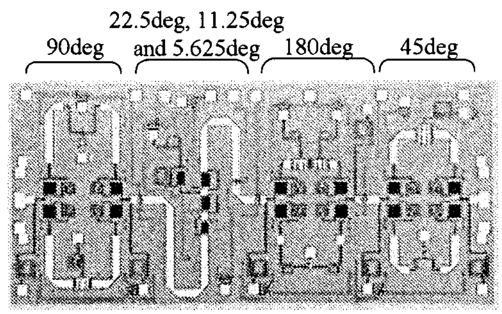



Fig. 17. $K$-band 6-bit p-HEMT PS MMIC.

a gain of 28.1 dB at 91 GHz [11].A millimeter-wave LNA is desirable for on-bo

Fig. 16 shows the state-of-the-art of noise-figure characteristics for millimeter-wave multistage amplifier/receiver modules, which are constructed using GaAs and InP device technologies [12]–[19]. From this figure, it is shown that the $K$- and $W$-band amplifier modules mentioned above have demonstrated fairly good performance of a low noise figure in module technology.

## V. PS MMICs

In recent years, APAAs or multibeam antennas have been widely proposed for on-board antenna systems, where a large number of PSs are used for beam steering. It is required that the PS used in these systems has small chip size and high performance.

Fig. 17 shows a $K$-band 6-bit p-HEMT PS MMIC. To reduce chip size, a novel matched embedded-FET PS configuration, shown in Fig. 18, is used for low bit sections. Measurements of the 6-bit PS have performed an average insertion loss of 7 dB, phase shift rms error of 5°, and amplitude rms error of 0.35 dB over 15.5–17.5 GHz [20].

We have developed a $K$-band 4-bit VDL module to realize variable delay performance in a wide frequency range in a large aperture APAA. Fig. 19 shows the VDL module, in which switch-bank MMICs and microwave-integrated-circuit (MIC) delay lines are mounted in an LTCC multilayered package. Fig. 20 shows the measured time-delay characteristics of the VDL module. The VDL module has demonstrated time-delay error of less than 45 p/s rms [21].

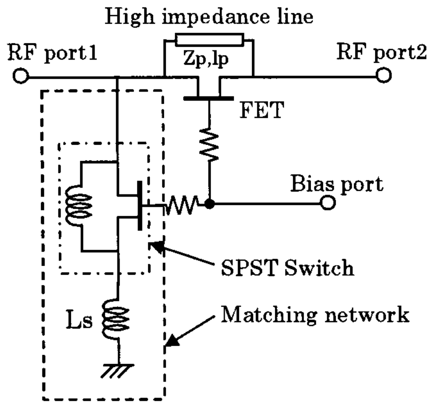



Fig. 18. Schematic diagram of the novel matched embedded FET PS configuration.

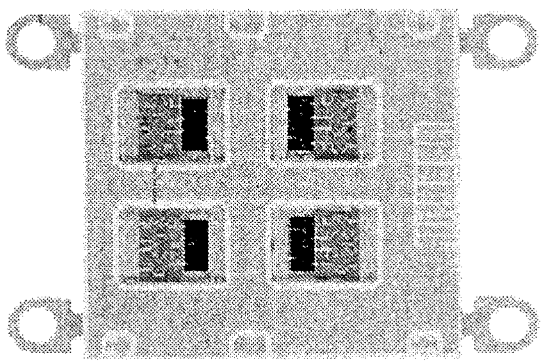


Fig. 19. $K$-band 4-bit VDL module mounted in an LTCC multilayered package.

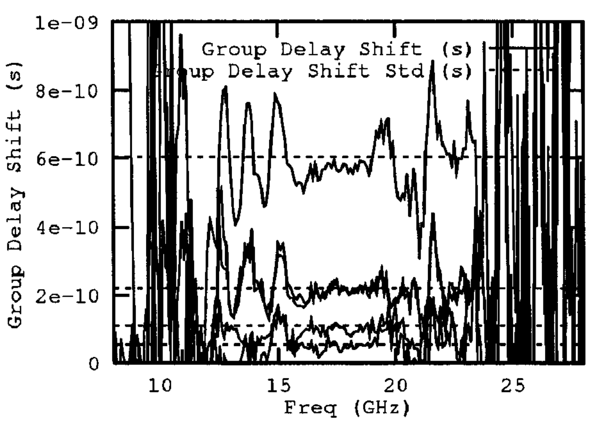
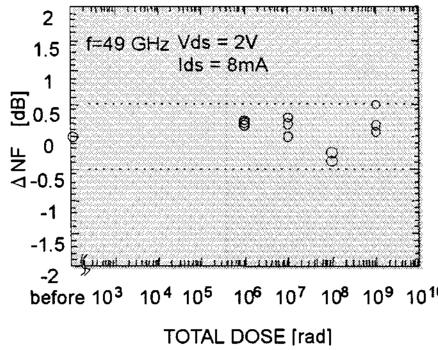


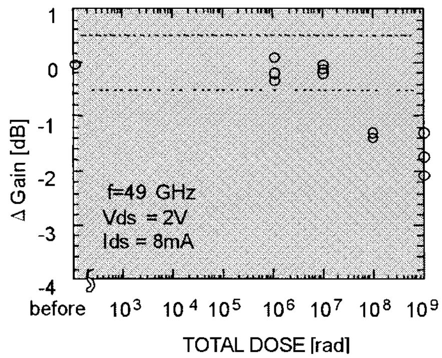

Fig. 20. Measured time-delay characteristics of the $K$-band 4-bit VDL.

## VI. Investigation for Gamma-Ray Irradiation on Millimeter-Wave p-HEMT MMIC

Gamma-ray irradiation hardness of a millimeter-wave low-noise p-HEMT MMIC amplifier was investigated for space-born application [22]. A gamma ray was irradiated to a 50-GHz-band low-noise p-HEMT MMIC amplifier with dc bias and the changes of RF performance were measured. Fig. 21 shows gamma-ray irradiated hardness of RF performance for millimeter-wave low-noise p-HEMT amplifier MMICs. No degradation of RF performance was observed up to $10^7$ rad dose. It suggests that millimeter-wave p-HEMT MMICs have




(a)




(b)

Fig. 21. Gamma-ray irradiated hardness of: (a) noise figure and (b) gain for millimeter-wave low-noise p-HEMT amplifier MMICs.

over 100 years of life against gamma-ray irradiation in the space environment.

## VII. Conclusion

Our latest millimeter-wave p-HEMT MMIC developments and technologies concerned with HPAs, LNAs, and PSs have been summarized. It has been shown that high-efficiency, low-noise, and low-loss performance for millimeter-wave space applications could be achieved by employing p-HEMT MMIC technology. From the investigation of the gamma-ray irradiation test, it was shown that millimeter-wave p-HEMT devices would have over a 100 years of life against gamma-ray irradiation in a space environment.

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