An Independently Biased 3-stack GaN HEMT Configuration for 5G Mobile Networks

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***Abstract*—In this paper, we propose an independently biased 3-stack GaN high electron mobility transistor (HEMT) configuration which can be utilized to design key amplifiers including microwave intermediate amplifier, low-noise amplifier and power amplifier of transceivers for 5G mobile networks. Both the small-signal and large-signal performance of the proposed configuration are investigated in comparison with other configurations including single stage, cascode and conventional 3-stack. The investigated results show that, thanks to the independently biased technique, the proposed configuration can offer better performance compared with other configurations. In term of small-signal performance, the proposed 3-stack configuration exhibits superior isolation, stability and maximum available gain. In addition, in term of large-signal performance it exhibits superior output power, power gain, efficiency and linearity over the other configurations. These superior performances are investigated at the 5G frequency bands. This makes the proposed circuit configuration to be an excellent candidate for designing important amplifiers of the 5G mobile networks.**

***Index Terms*—5G, GaN HEMT, power amplifier, independently biased**

I. Introduction

The fifth generation (5G) mobile network [1] [2], the latest mobile network communications is becoming important in the real life. In the 5G network, one of critical requirements is high-capability communications. High-capability communications is feasible if carrier frequency is increased to be higher than that of the present 4G network to support wider bandwidth. The lower frequency range of 5G should be from 3 GHz to 6 GHz while the upper frequency range should be higher than 24 GHz. Design of key components of 5G transceiver system such as intermediate amplifier, low-noise amplifier and power amplifier face challenging issues when designed at higher frequencies. This is due to inherent drawbacks of transistor such as low isolation, low gain, low output power and low linearity when operating at high frequencies. Therefore, it is important to find out alternative circuit configurations which can offer superior characteristics at both small-signal (SS) and large-signal (LS) level to design good amplifiers for use in 5G mobile network. It is widely known that stacked transistor configuration such as cascode or Darlington can offer promising advantages over single-stage transistor. The cascode configuration for bipolar junction transistor (BJT)-type which connects the first common emitter (CE) transistor and the second common base (CB) transistor or field effect transistor (FET)-type which connects the first common-source (CS) transistor and the second common-gate (CG) transistor [3] has high-frequency operation, high gain and high isolation features. The Darlington configuration [4] can offer high current gain but it cannot operate efficently at high frequency. These well-known configurations may become promising candidates for the design of 5G circuit components. However, one major drawback of theirs is that the common point between two transistors is a floating potential. This causes a serious problem of not be able to independently adjust operation condition for each transistor. To surmount this, an additional bias terminal is inserted into this common point [5]. This technique ensures that operation condition of each transistor can be controlled independently, resulting in an ability of improving various performances simultaneouly at both SS and LS regime. The advantages of using such a technique has been demonstrated in [5] [6]. However, in these articles improvement of output power and efficiency as well as linearity has limitations. In order to further enhance various performances based on similar technique, we propose

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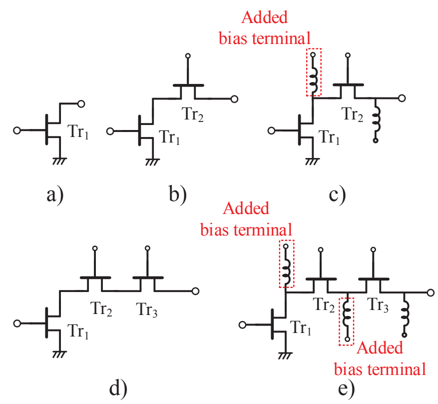

Fig. 1. Circuit configurations: a) single-stage; b) conventional cascode; c) independently biased cascode; d) conventional 3-stack; e) independently biased 3-stack.

an independently biased 3-stack GaN HEMT configuration. This configuration is realized by extending the independently biased cascode configuration through connecting it with an additional CG transistor. Fig. 1 illustrates such a circuit along with other circuit configurations to be investigated. As can be clearly seen in the figure, the independently biased 3-stack configuration is realized by connecting the independently biased cascode with a third CG transistor. In addition, another additional bias terminal is also inserted to the floating point between the last two transistors. By inserting the two additional bias terminals, operation condition of three transistors can be freely adjusted which cannot be done in conventional configurations. This helps to optimize both SS and LS characteristics effectively by adjusting bias condition of each individual transistor appropriately. Nevertheless, it is worth noting that if the number of transistor increases more, parasitic components will take effect seriously at higher frequencies limiting both SS and LS performance improvement. Although advantages of the independently biased 3-stack configuration has been investigated for BJT-type transistor or HBT in [7], the investigation for HEMT devices and at 5G frequency band has never been conducted before. In addition, we aim to use the monolithic microwave integrated circuit (MMIC) technology to make the independently biased 3-stack GaN HEMT chip. This helps to reduce the circuit size. The paper is organized as follows: Sec. II presents SS such as reverse isolation, maximum available gain (MAG) and stability investigation of the proposed configuration in comparison with other ones while Sec. III will investigate LS performance including output power, power gain, efficiency and linearity of the proposed configuration; Sec. IV will conclude the paper.

II. Small-Signal Investigation

In this section, SS characteristics including reverse isolation, MAG and stability of the proposed configuration is investigated in comparison with other configurations. The investigations are conducted based on a simulation method using a Keysight ADS simulator. The SS performances play a key role for designing intermediate amplifier and low-noise amplifier at both lower and higher frequency ranges of the 5G network. Bias condition for all configurations are indicated in Table I. Here, it is important to note that the configurations are biased at class-A for the purpose of SS investigation. As shown in the table, conventional configurations cannot set bias condition independently for each transistor. Fig. 2 describes the simulation setup in the Keysight ADS simulator for simulation of S-parameter of configurations. Although the figure shows the simulation setup for the proposed 3-stack GaN HEMT configuration, that of the other configurations are set up in a similar way.

A. Reverse isolation characteristic

Reverse isolation is an important parameter when designing microwave amplifiers and especially low-noise amplifiers (LNAs). It is evaluated in term of scattering parameter S_{12} of a two-port network. If one two-port has higher isolation

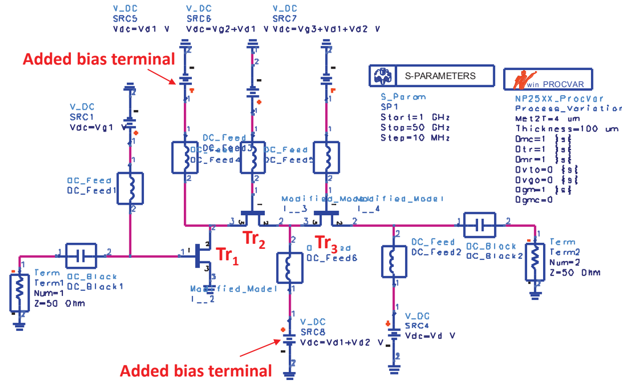

Fig. 2. Simulation setup in the Keysight ADS for SS investigations.

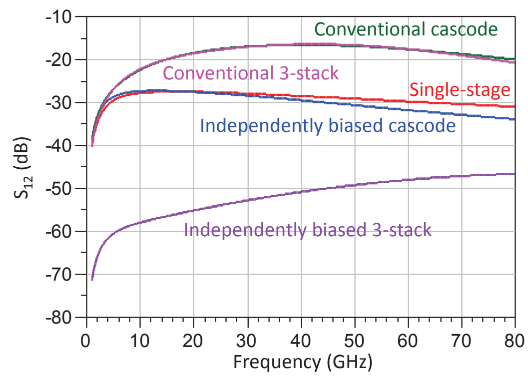

Fig. 3. Reverse isolation characteristic.

TABLE I
Bias condition of configurations for SS investigation.

Configurations	V_{g1}	V_{g2}	V_{g3}	V_{d1}	V_{d2}	V_{d3}
Single-stage	-2V	X	X	44V	X	X
Conventional cascode	-2V	-2V	X	X	44V	X
Independently biased cascode	-2V	-2V	-2V	5V	44V	X
Conventional 3-stack	-2V	-2V	-2V	X	X	44V
Independently biased 3-stack	-2V	-2V	-2V	1V	3.5V	44V

or smaller S_{12}, it is better. It is expected that the 3-stack with independently biased feature will offer the best isolation among the configurations thanks to the independently biased technique. Fig. 3 which shows the isolation of the configurations confirms this fact. As can be seen in the figure, at both 5G frequency bands, isolation of the proposed configuration is remarkably higher than the other configurations. Here, the isolation of the proposed 3-stack is mainly dependent on the first gate bias. Hence, it will be utilized for the purpose of isolation improvement.

B. Stability characteristic

In this section, stability of the configurations is evaluated using μ criteria. It is expressed in term of scattering parameters

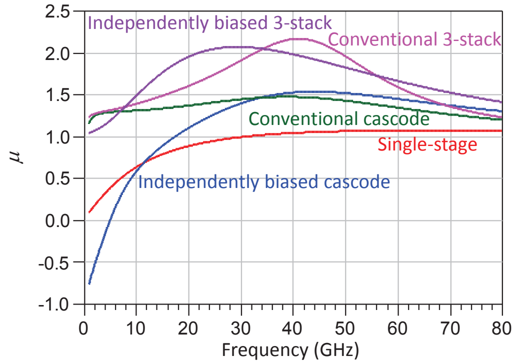

Fig. 4. Stability characteristic.

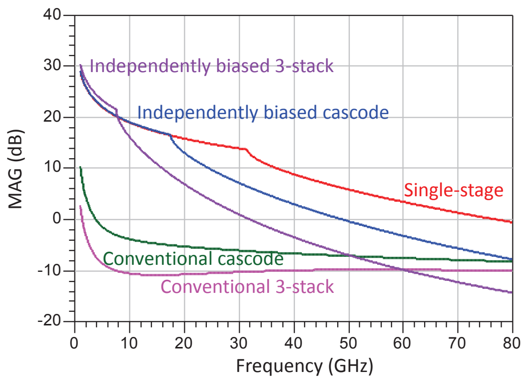

Fig. 5. Power gain characteristic.

of a two-port network by the following formula [8]:

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}^*| + |S_{12}S_{21}|} \tag{1}$$

The μ criteria is measure of stability and it indicates that if one two-port has larger μ, it is more stable. Moreover, if one two-port is stable, μ has to be greater than unity. Therefore, this criteria is usually used to compare stability between two-port networks. Fig. 4 which shows stability of configurations indicates that the independently biased 3-stack configuration is stable in entire frequency range from 1 GHz to 80 GHz which covers both 5G frequency bands. In addition, its stability is higher than most of the other configurations. Stability of this configuration mostly depends on the second gate bias. For this reason, the second gate bias is used to improve the circuit stability. Although the conventional 3-stack exhibits higher stability than the proposed 3-stack configuration at some frequency points, its isolation is very poor as shown in Fig. 3.

C. Power gain characteristic

In order to compare power gain among the configurations, MAG will be used. This power gain is given by following formula [8]:

$$\text{MAG} = \frac{S_{21}}{S_{12}}\left(K - \sqrt{K^2 - 1}\right) \tag{2}$$

where K is Rollett stability factor and is expressed through the scattering parameters as:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2\,|S_{12}S_{21}|} \tag{3}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \tag{4}$$

MAG of the proposed configuration is mainly contributed by the gate and drain bias or the operation condition of the first transistor. Hence, the first gate and drain bias terminal are the main parameters for the power gain improvement. Fig. 5 indicates that below 8 GHz MAG of the proposed configuration is highest. However, at higher frequencies the power gain drops more sharply than that of the independently biased cascode and single-stage configurations. This is caused by the additional parasitics of the the 3-stack configurations at higher frequencies. This effect of the parasitics also limits the maximum oscillation frequency (f_{max}) of the proposed 3-stack configuration. The figure shows that f_{max} of the proposed 3-stack is around 32 GHz while that of the independently biased cascode and single-stage are 49 GHz and 78 GHz, respectively. The conventional cascode and conventional 3-stack configurations exhibit poorest MAG since their operation condition cannot be tuned. Here, it is noted that, for a fair comparison among configurations the total drain bias voltage of all configurations is set equally.

From the above SS investigation, advantages of the proposed 3-stack configuration has been clarified in term of reserve isolation, stability and MAG. These performances can be optimized by utilizing independently biased technique. The first gate and drain biases contributes the improvement of isolation while the second gate bias contributes the improvement of stability. This means various SS characteristics of the proposed 3-stack configuration can be improved simultaneously.

III. Large-signal Investigation

In this section LS performance including output power, power gain, efficiency and linearity of the configurations are investigated. Among these LS performances, efficiency which is expressed in term of power added efficiency (PAE) and linearity which is expressed in term of third-order inter-modulation (IMD3) are critical factors when designing power amplifiers for 5G mobile networks. For a fair and logical comparison when operating in the LS regime, bias condition of each transistor of the independently biased configurations including independently biased cascode and independently biased 3-stack is adjusted freely to obtain their best performance. The conventional configurations including single-stage, conventional cascode and conventional 3-stack cannot do this due to the lack of the additional bias terminals. Here, the LS investigation is conducted at a frequency of 3.5 GHz which falls into the lower frequency band of the 5G mobile network. The GaN HEMT LS model is provided by WIN Semiconductor Inc. The simulation setup implemented in the Keysight ADS for LS simulation of the configurations is shown in Fig. 6. Although the figure shows the simulation setup for PAE simulation of the proposed 3-stack GaN HEMT

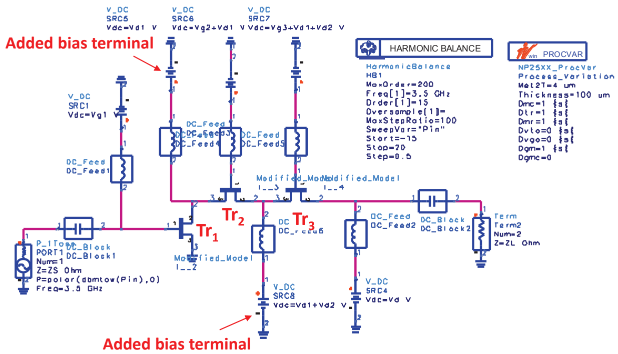

Fig. 6. Simulation setup in the Keysight ADS for LS investigations.

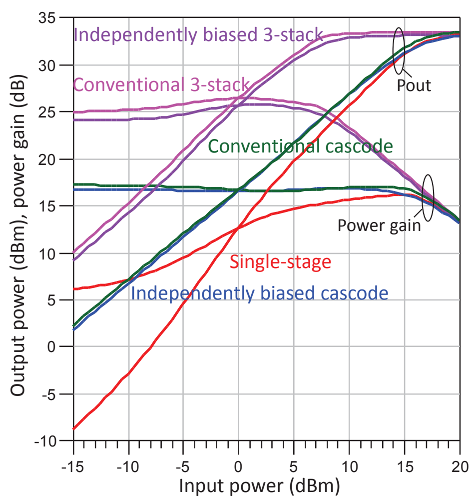

Fig. 7. Output power and power gain characteristics.

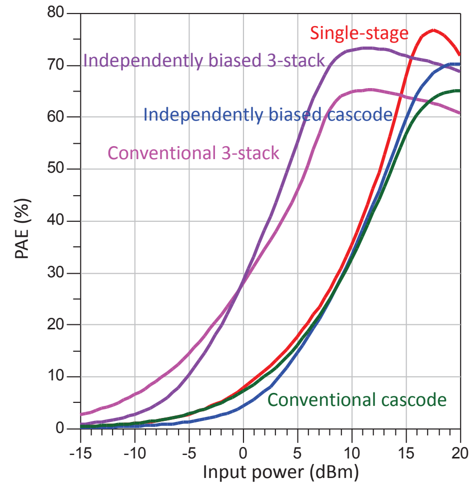

Fig. 8. Efficiency characteristics.

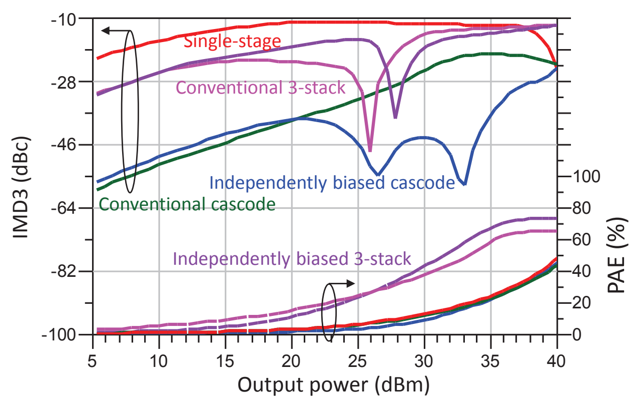

Fig. 9. Linearity (IMD3) characteristic.

configuration, simulation setup for IMD3 is performed by replacing the one-tone power source in the schematic with a two-tone power source. In addition, the simulation setup for the other configurations are implemented in a similar way.

A. Output power and power gain

Fig. 7 shows the comparison in output power and power gain among the configurations. Obviously, single-stage and cascode configurations have significantly low power gain and output power compared with that of the 3-stack configurations. The proposed 3-stack configuration has similar output power and power gain as that of the conventional 3-stack one. Both of them have highest output power and power gain compared with other configurations. This is because the 3-stack configurations can deliver higher output voltage swing capability. Although both the 3-stack configurations have similar output power and power gain, efficiency of the conventional 3-stack one is poorer than that of the proposed 3-stack one as indicated in Fig. 8. As shown in the figure, the proposed 3-stack has superior efficiency among the configurations. The efficiency of this configuration is controlled by the third drain bias voltage (V_{ds3}). Hence, to improve efficiency this bias terminal must be tuned.

TABLE II
OPTIMUM LOAD/SOURCE IMPEDANCES OF CONFIGURATIONS.

Configurations	Source impedance	Load impedance
Single-stage	22.3+j31.2	233+j273
Conventional cascode	56+j293	223.2+j250
Independently biased cascode	56+j293	223.2+j250
Conventional 3-stack	55.9+j101	179+j273
Independently biased 3-stack	55.9+j101	179+j273

B. Efficiency and linearity

It is noted that efficiency of each configuration is obtained by using a load/source pull technique based on the LS GaN HEMT model to find out their optimum load/source impedances. These optimum impedances for each configuration are shown in Table II. Moreover, bias condition of each configuration is given in Table III. In contrast to the SS investigation in which operation condition is set at class-A, in LS investigation operation condition of transistor are set at class-AB since they operate in the non-linear regime. Along

TABLE III
BIAS CONDITION OF CONFIGURATIONS FOR LS INVESTIGATION.

Configurations	V_{g1}	V_{g2}	V_{g3}	V_{d1}	V_{d2}	V_{d3}
Single-stage	-2.6V	X	X	44V	X	X
Conventional cascode	-2.6V	-2.6V	X	44V	X	X
Independently biased cascode	-2.6V	-2.6V	X	6V	44V	X
Conventional 3-stack	-2.6V	-2.6V	-2.6V	X	X	44V
Independently biased 3-stack	-2.6V	-2.6V	-2.6V	5V	4V	44V

TABLE IV
SUMMARY OF LINEARITY AND EFFICIENCY.

Configurations	IMD3 level	PAE
Single-stage	-35 dBc	X
Conventional cascode	-35 dBc	4.5%
Independently biased cascode	-35 dBc	22.8%
Conventional 3-stack	-35 dBc	25%
Independently biased 3-stack	-35 dBc	35%

with efficiency, another critical performance when designing power amplifier is the linearity which can be evaluated in term of IMD3 parameter. In this paper, IMD3 is tested at a center frequency of 3.5 GHz with a frequency spacing of 4 MHz. In Fig. 9 which shows IMD3 performance of the configurations corresponding to their efficiency. In IMD3 test for 5G mobile applications, the limit level of IMD3 is taken at -35 dBc. The figure shows that IMD3 of the single-stage cannot reach this level. However, the remaining configurations can reach this level with respect to their corresponding efficiency. Summary of this behavior is demonstrated in Table IV. It can be seen that at the IMD3 level of -35 dBc, the proposed 3-stack configuration has highest efficiency of 35%. This confirms the advantage of the proposed configuration in term of both efficiency and linearity.

IV. CONCLUSIONS

In this paper, an independently biased 3-stack GaN HEMT configuration has been proposed for design of critical amplifiers in 5G mobile network. Its SS and LS performance has been investigated and improved thanks to the use of the independently biased technique. SS investigation indicates that the proposed 3-stack configuration can offer better isolation, stability and MAG over the other configurations when controlling the gate bias terminals. Although inherent parasitics limit $f_{\max}$ of the proposed configuration, it is still suitable for using in frequency band of the 5G mobile network. Additionally, In LS investigation at 3.5 GHz, the proposed configuration offers superior output power, power gain and linearity over the other configurations. This is achieved when adjusting the drain bias terminals. These investigations demonstrate that the proposed 3-stack configuration can be efficiently applied to design various components of both transmitter and receiver of 5G mobile networks including intermediate amplifier, low-noise amplifier and power amplifier.

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