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Influence of a graded channel HEMT on the performance of Class BJF^{-1} amplifiers for 5G applications

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Abstract

We explore the benefits of continuum mode amplifier design using a graded GaN HEMT structure operating at a low drain bias of 5V to meet requirements of efficiency, linearity and bandwidth in 5G mobile networks. A significant increase in the available design space for high-efficiency is observed in the graded-channel device when compared to a conventional GaN HEMT, revealing the advantages of broad bandwidth, over and above improvement of 20-30 dB in linearity due to the intrinsic flat transconductance and linear gate capacitance characteristics of the graded device.

Introduction

Efficiency, linearity and bandwidth remain critical challenges for realizing amplifiers with increasingly complex modulation schemes (e.g. 64-QAM and higher) for 5G communications. These require advancement at both the device and circuit level, particularly to displace GaAs device technologies that operate at lower drain bias voltages compared to typical GaN devices. The high efficiency benefits of GaN are particularly important at higher operating voltages, although conventional GaN HEMTs can have linearity challenges. In this regard, GaN HEMTs with graded channels have been shown to achieve high linearity and efficiency even at low operating voltages [1]. These can be combined with continuum modes that are beneficial in achieving tolerance to impedance mismatch whilst delivering high efficiency over large bandwidths [2][3]. In this work, we undertake a modelling study of a continuum mode amplifier design using a graded-channel GaN HEMT device operating at a drain bias of 5V at 38 GHz.

Background

Continuum mode amplifiers are interesting because of the large choice of embedding impedances which results in inherently broadband characteristics. The first proposed continuum mode, class B/J/J* [4], relies on manipulation of the fundamental and second harmonic components of the voltage waveform of class B depending upon the parameter α, while the current waveform is unchanged as plotted in Figure 1 (a). The efficiency of all the waveforms in the figure remains the same because the increase in the fundamental component of the voltage is counteracted by the additional phase shift which increases the overlap of the voltage and current. For instance, the voltage waveform for $\alpha = 1$ (referred to as class J) has the highest fundamental component as well as the highest overlap. The main

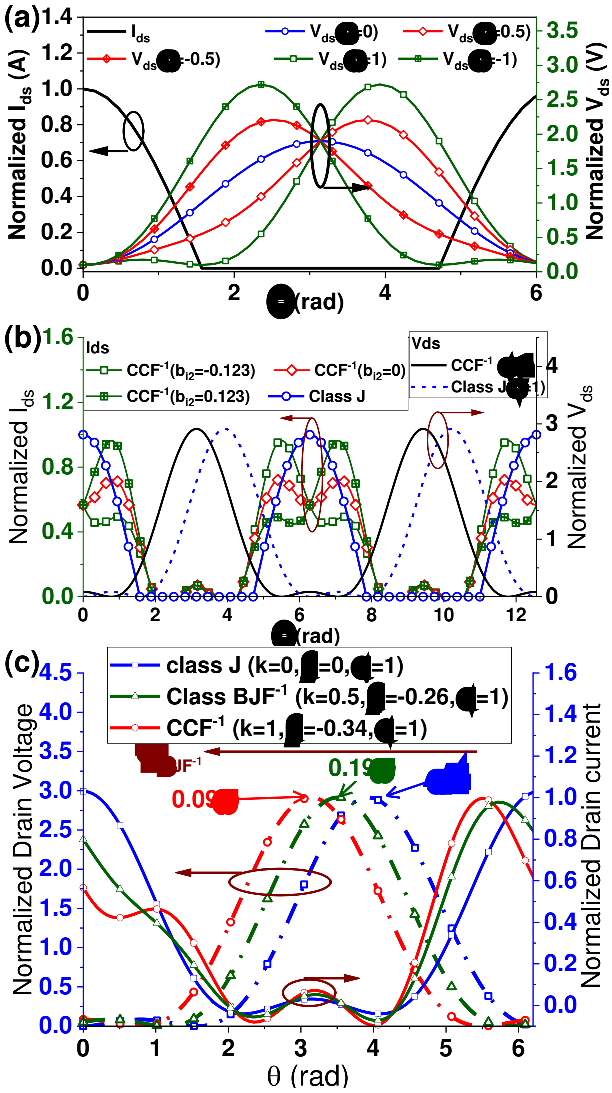

Figure 1. (a) Voltage and current plots of the Class B/J/J* continuum. (b) Comparison of the class J with continuous class F^{-1}. (c) Comparison of voltage and current waveforms of Class J, CCF^{-1}, and Class BJF^{-1}.

advantage of Class B/J/J* is an increase in the design space.

On the other hand, the voltage and current waveform of continuous class F^{-1} (CCF^{-1}) [5][6] which relies on manipulation of the second harmonic of the current waveform are compared with Class J in Figure 1 (b). The current waveform marked $b_{i2} = 0$, corresponding to Class F^{-1}, has zero second harmonic component (both the in-phase (a_{i2}) and quadrature (b_{i2}) components are null), whereas the voltage has a phase shift when compared to class J. This reduction of overlap between the current and

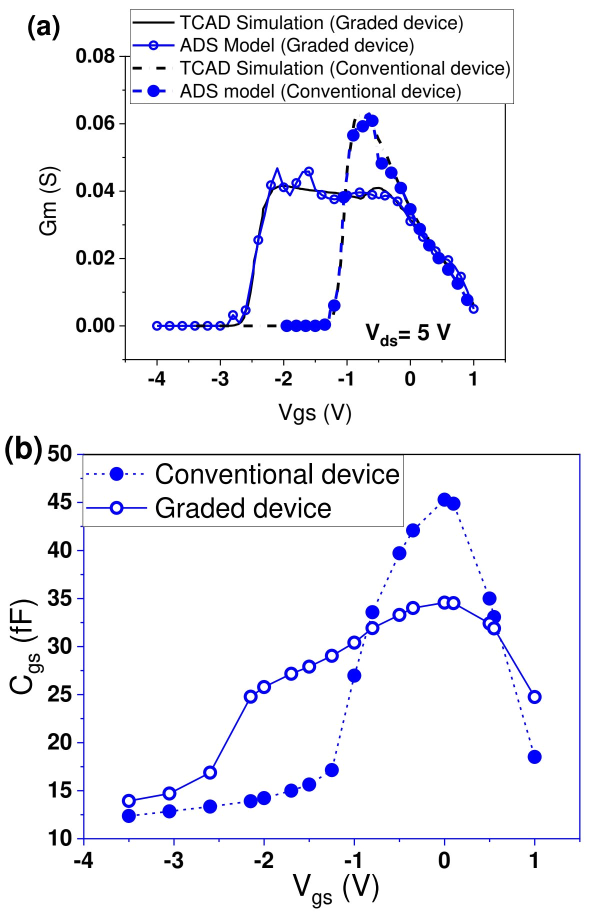

Figure 2. The transconductance and gate capacitance (C_{gs}) characteristics of graded and conventional HEMT devices are compared in (a) and (b) respectively.

voltage waveform in class F^{-1}, results in an improvement of efficiency from 78.5 % in class J to 91% in class F^{-1}. Varying the quadrature components (b_{i2}) of the second harmonic results in current waveforms of CCF^{-1}, all achieving 91 % efficiency in theory.

The in-phase component (a_{i2}) of the current waveforms is null in CCF^{-1} whereas its magnitude is the highest along the Class B/J/J* continuum. A set of current waveforms in which a_{i2} is only a factor (k) of its magnitude in the Class B/J/J* continuum were proposed by us in [2]. This set of waveforms lies in-between Class CCF^{-1} and Class B/J/J*; an example is shown in Figure 1 (c). The impedances calculated based on these waveforms cover a larger design space than either the CCF^{-1} and Class B/J/J* alone. Additionally, the tuning of third and higher harmonics, required in Continuous Class F (CCF) is not required for this class, clearly increasing its attractiveness for 5G applications above 30 GHz, where characterisation at the third harmonic is a significant challenge.

It is important to note that the voltage and current waveforms are related via the IV characteristics of the device. The manipulation of the second harmonic component of the current as required for class F^{-1}, CCF^{-1}, and Class BJF^{-1} requires harmonic contribution from the non-linearity of the knee region of the IV and the second harmonic from the intrinsic capacitance, as illustrated in [7].

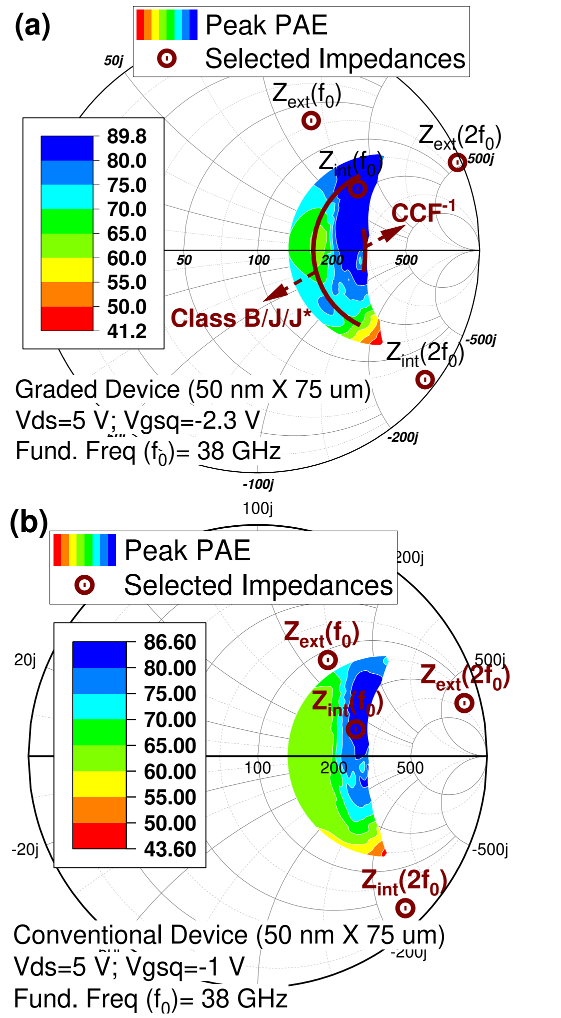

Figure 3. The peak efficiency of graded and conventional GaN HEMTs simulated over the class BJF^{-1} continuum in (a) and (b) respectively.

Device Modelling

The graded and conventional devices of W x L= 75 x 0.050 µm² were modelled and simulated in Synopsys Sentaurus TCAD to obtain the IV and S-parameters for a set of bias points between the threshold and saturation gate voltages, while the drain voltage was swept from 0 V to 5 V. The equivalent circuit model for each of these devices is extracted for amplifier simulation in ADS. The IV is modelled using a table-based approach whereas the non-linear intrinsic-capacitances (gate-source (C_{gs}), drain-source (C_{ds}), and gate-drain (C_{gd})) are extracted from the S-parameters using the approach described in [7].

Results and discussion

The transconductance and the gate capacitance of the graded and conventional HEMT devices plotted in Figure 2 (a) and (b) respectively. The close match between the g_m in TCAD and modelled g_m in ADS reveals accuracy of the ADS model in both cases. The comparison reveals that graded devices have a flat transconductance when compared to the conventional HEMT device, which has a sharp peak in g_m. Additionally, the graded device demonstrates a more linear gate capacitance when compared to that of a

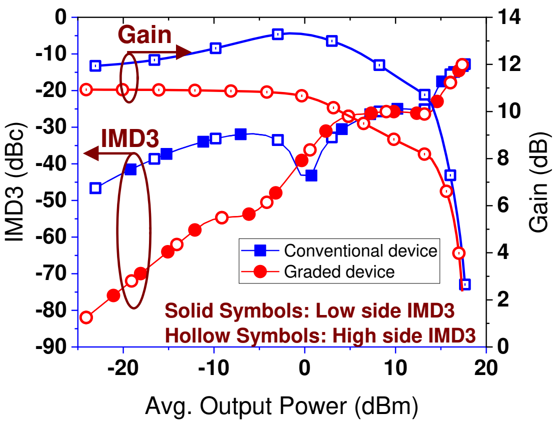

Figure 4. Comparison of the IMD3 and the Gain of the graded and conventional devices for the two-tone signal centred at 38 GHz with the tone separation of 200 kHz. The load impedances were set to those marked in Figure 2.

conventional device. This explains the high linearity of the graded device.

The simulated peak efficiency of both the graded and conventional devices is plotted over the class BJF^{-1} design space in Figure 3. The impedances at fundamental frequency of class B/J/J* continuum and CCF^{-1} are plotted in Figure 3(a). It can be seen that a large set of impedances with efficiency greater than 80 % belong neither to class B/J/J* continuum nor to CCF^{-1}. illustrating the benefit of Class BJF^{-1}. Moreover, comparing Figures 3 (a) and 3(b), it can be seen that an efficiency greater than 80% can be achieved over a larger set of impedances for the graded device as compared to the conventional device, with a peak PAE higher than that of the conventional device by 3%. This wide choice of embedding impedances indicates inherent flexibility in amplifier design and tolerance to variation in device processing and matching network realization.

The linearity of both devices is examined using a two-tone signal whose centre frequency is 38 GHz with a tone separation of 200 kHz. For this simulation, the load impedances were selected from the high-efficiency region of the graded and conventional HEMT devices and selected impedances at the intrinsic plane and the corresponding extrinsic impedances are shown in Figure 3. The source impedances were set to 50 Ω and all the harmonics and baseband impedances were shorted for both devices.

The obtained IMD3 and gain of the graded and conventional devices are compared in Figure 4. The conventional HEMT shows a significant gain expansion whereas the graded shows a flat gain up to 0 dBm beyond which it shows a soft gain compression. A significant improvement in IMD3 of the graded device is observed up to an output power of 0 dBm. At low power levels, the distortion generated from the current generator (IV of the device) dominates the IMD3 [8]. Hence, this significantly lower IMD3 and flat gain can be attributed to the flat g_m and linear gate capacitance of the graded device seen in Figure 2. However, the ungraded device shows a slight improvement from 0 dBm and 10 dBm. Beyond 10 dBm, both devices demonstrate similar IMD3 because the amplifiers saturate (the load line enters the knee region of the device) due to hard compression. This shows that designing class BJF^{-1} amplifiers using the graded-channel device simultaneously achieves high efficiency and better linearity when compared with a conventional GaN HEMT.

Conclusions

This work reveals the benefits of using continuum mode (class BJF^{-1}) using GaN HEMTs with a graded channel, operating at a low bias of 5V, resulting in higher efficiency over a broader bandwidth with a greater tolerance to mismatch. In addition, the flat g_m and more linear gate capacitance of the graded device results in a significantly improved IMD3 when compared with a conventional device.

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