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Broadband CMOS Stacked RF Power Amplifier for Low Power Wideband Envelope Tracking

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ABSTRACT

Non-Foster matching is applied to design a multi- octave broadband GaN power amplifier (PA) in this work. The bandwidth limitation from high-Q interstage matching is mitigated through the use of negative capacitor, which is realized with a negative impedance converter (NIC). Detailed analysis is presented to understand the frequency and power limits of NIC circuits for PA application. A 6-18 GHz power amplifier fabricated with 0.25-μm GaN pHEMT process shows the output power reaching 35.7-37.5 dBm with 13-21% PAE. The NIC boosts the efficiencies and power below 11 GHz to achieve broadband performance without the use of any lossy matching circuits or negative feedback. To our knowledge, this is the first demonstration of NIC-based broadband amplifiers with Watt- level output power.

INTRODUCTION

A watt-level power amplifier (PA) with multi-octave bandwidth is essential for the broadband applications like electronic warfare. GaN device is suitable for this case due to its high power density and high voltage operation, which results in relatively large load impedance. The distributed amplifiers (DAs) and reactive matched PAs (RMPAs) are widely used as multi-octave PAs. However, DA suffers from small gain, and RMPA typically requires large chip size and has difficulty in achieving the required gain flatness over a wide bandwidth. Reconfigurable matching concept has also been proposed for multi-stage PAs to overcome the bandwidth limitation coming from high-Q interstage matching. However, the switch loss degrades the PA efficiency (S. Park *et al.*, 2014). A potential alternative for wideband matching is the use of a non-Foster circuit (NFC). The first non-Foster circuit using the transistors was designed (J. Linvill J. 1953). The NFC was used to compensate for the parasitic effects of various circuits such as filters, varactors and VCOs (Q. Wu *et al.*, 2013). For example, the negative slope of the reactance versus frequency is used to overcome the limitation of the antenna size and Q-factor at 800 MHz (O. Tade *et al.*, 2013). DA gain-bandwidth enhancement has been demonstrated using the negative capacitance in (A. Ghadiri *et al., 2010*). However, its application was limited to small-signal applications. There are three major challenges using non-Foster circuit for broadband circuits, noise, stability and power handling capability. Due to the power handling issues, little work has been presented to demonstrate a broadband PA using non-Foster circuit.

In this work, a 5 W 6-18 GHz GaN power amplifier has

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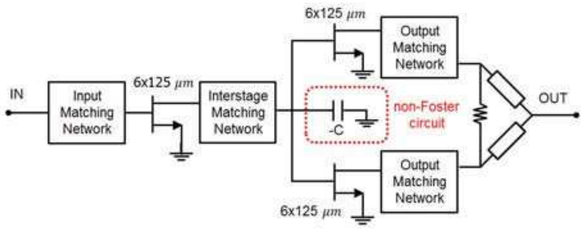


Fig. 1: Block diagram of the two-stage PA with non-Foster matching network.

been developed using non-Foster circuit in the interstage matching to achieve multi-octave power bandwidth.

Interstage Matching With Nic:

A simplified block diagram of the two-stage GaN PA with the proposed non-Foster circuit is shown in Fig. 1. The unit FET size of the PA is 6×125 μm, which has a maximum available gain (MAG) of 12 dB at 18 GHz. To achieve overall gain higher than 15 dB, a two-stage design is required, in which case the bandwidth limitation often comes from the high-Q interstage matching rather than the output matching. In this work, the NFC is employed in the interstage matching to cancel out the large input capacitance of the power-stage FETs, lowering the Q-factor of interstage matching.

The output matching is composed of a conventional two- section matching network and the output powers from each FET are combined through a Wilkinson power combiner to achieve 36-dBm output power over the target frequency range of 6-18 GHz. In theory, the addition of NFCs in the output matching network can further improve the power bandwidth. However, the power handling capability of NFC has to scale with the RF power, which increases the DC power consumption of NFC and degrades the PAE of the overall PA. Therefore, in this work, NFC is employed in the interstage matching only.

Another practical issue with NFC is the limited operating frequency; the bandwidth limitation comes from the self- resonating frequency (SRF), which is limited by f_T of the device. GaN FETs have a gate length of 0.25 μm and the NFC using these FETs show self resonance around 11 GHz, which is not high enough to cover the entire bandwidth up to 18 GHz. So, the interstage matching network is optimized separately for two sub-frequency regions. Natural interstage matching is optimized for the upper sub-frequency band above 11 GHz,

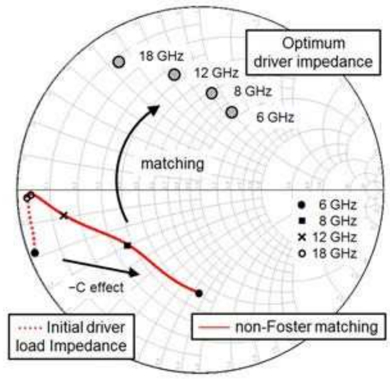
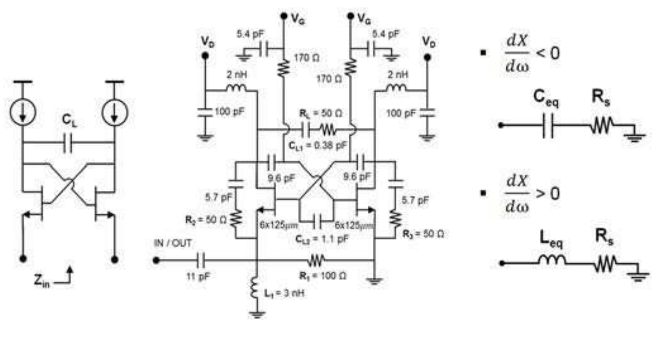


Fig. 2: Simulated interstage impedance matching with NFC.



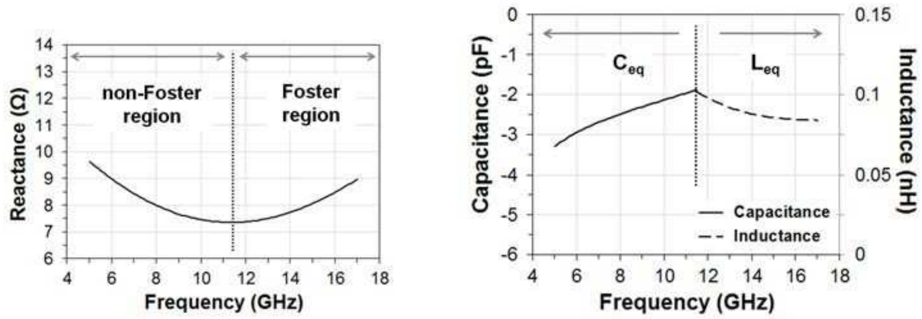
(a) (b) (c)

Fig. 3: (a) Linvill's NIC block diagram, (b) the detailed schematic of the proposed NIC, and (c) the simplified equivalent of the NIC

where the negative capacitance is not available. The subsequent power mismatch in the low sub-frequency band is compensated by the negative capacitance presented by NFC.

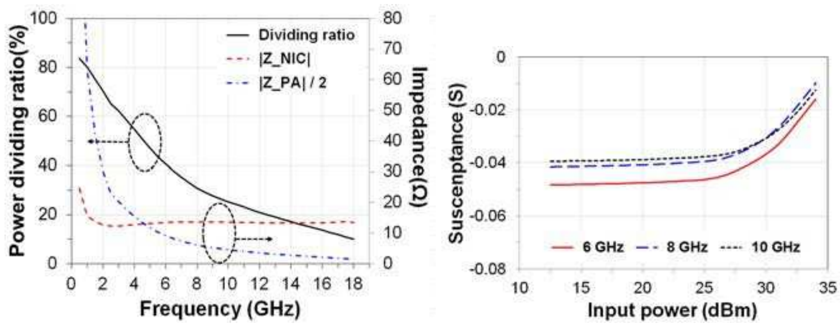
To better understand the benefit of NFC in the interstage matching, the input impedance of the power stage is simulated together with the optimum load impedance of the driver-stage FET in Fig. 2. The optimum driver-stage impedance moves along a constant-g circle in counter-clockwise direction as the frequency increases. The input impedance of the power stage is highly capacitive due to the large input gate capacitance of 1.4 pF. It is thus very difficult to provide optimum impedance matching across the entire bandwidth. Upper frequencies above 11 GHz are matched using an inductive line and shunt stubs. The impedance mismatch in the lower frequency sub- band is solved by employing a negative shunt capacitance of –2.5 pF, which basically reduces the Q-factor of the input impedance of the power stage impedance from 10.30 to 1.62 at 6 GHz and 4.39 to 0.78 at 8 GHz. In this way, the same matching circuit consisting of the inductive line and the shunt inductance can be used to match the lower sub-band frequencies below 11 GHz as well.

The non-Foster circuit used in the interstage matching is based on the Linvill's negative impedance converter (NIC) (Fig. 3(a)). The detailed schematic of NIC is shown in Fig. 3 (b). The NIC is composed of the cross-coupled FETs with capacitors, resistors and inductors. The resistor R_1, R_2, and R_3 are used to prevent instability. The main operation of the NIC



(a) (b)

Fig. 4: Simulated (a) reactance of the NIC as a function of frequency and (b) equivalent capacitance or inductance.



(a) (b)

Fig. 5: (a) Simulation results of the power division ratio between the NIC and power stages. (b) Simulated susceptance of the NIC versus injected RF power.

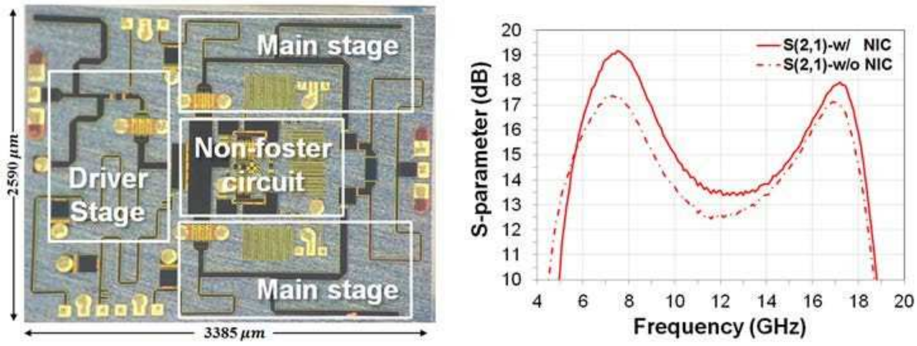
is to invert the polarity of C_L to an effective capacitance, C_{eq} ($= -k\, C_L$). The coefficient, k, is a function of the frequency since the actual equivalent circuit is much more complicated than a simple capacitor; it is composed of series and parallel resistances, parasitic capacitances and inductances, which cannot be neglected at microwave frequencies. For analysis, it is useful to represent the NIC with a simplified equivalent circuit of a series resistor (R_S) and either negative capacitance (C_{eq}) or inductance (L_{eq}), depending on the frequency, as shown in Fig. 3(c).

The simulated frequency-dependent reactance of the NIC is plotted in Fig. 4. The reactance decreases as the frequency increases up to 11 GHz, which clearly shows non-Foster characteristics. The equivalent capacitances of the NIC in this frequency range are up to −1.9 pF. The equivalent series resistance varies between 4.4 and 11.4 Ω. Above 11 GHz, where the self resonance occurs, the positive reactance slope is observed and the circuit follows Foster's theorem. In this case, the NIC is represented with a series combination of a resistance and a positive inductance as shown in Fig. 3(c).

Another limitation in NIC operation may come from the power handling capability in the PAs. The NICs cease to show negative impedance when they are driven with large RF power. As shown in Fig. 1, NIC shares the same node as two power- stage FETs. The RF power from the driver stage is divided into three paths with a different ratio depending on the operating frequencies. Fig. 5(a) shows the simulated power division ratio between the power stages (two FETs) and a NIC. As the frequency decreases, more power is delivered to the NIC than to the power stages, which can reduce the loop gain in the NIC below a threshold level required to generate the negative impedance. If the output power is 5 W and the power gain of the main stage is 3 dB, than the power delivered to each NIC is 0.125-0.5 W across the 6-18 GHz frequency band. To show the power handling capability, we have simulated the large-signal response of the NIC in Fig. 5(b). The negative susceptance, which is required to cancel out the positive susceptance due to the large power-stage input capacitance, decreases rapidly as the power increases. Combining the results of Fig. 5 (a) and Fig. 5(b), it is predicted that NIC will be no longer effective below ~ 6 GHz. So, it is expected that the effective frequency range of the NIC in our PA is limited to 6-11 GHz, corresponding to the previously mentioned “low-frequency sub-band”.

Measurement Results:

A two-stage broadband PA with the proposed non-Foster circuit is fabricated using a commercial 0.25-μm GaN pHEMT foundry process. Fig. 6(a) is the die photograph of the fabricated PA. As a reference, we have also tested the PA without NIC. The tests were performed by RF probe under continuous wave conditions and a test fixture with eutectic bonding was used for mitigating the self-heating of the PA. The test fixture was composed of a 5-mm-thick Au-plated Cu carrier and heat sink with thermal grease. The drain bias voltage to the PA is 28 V while that to the NIC is 15 V. Fig. 6(b) shows the measured small-signal gain with and without the NIC. Although the S11 and S22 remain almost same with and without the NIC, S21 increases by up to 2 dB in the lower-frequency sub-band from 6 to 11 GHz with the NIC.



(a) (b)

Fig. 6: (a) Fabricated chip photograph of the PA with NIC. (b) Measured small-signal gain of the PA with and without the NIC.

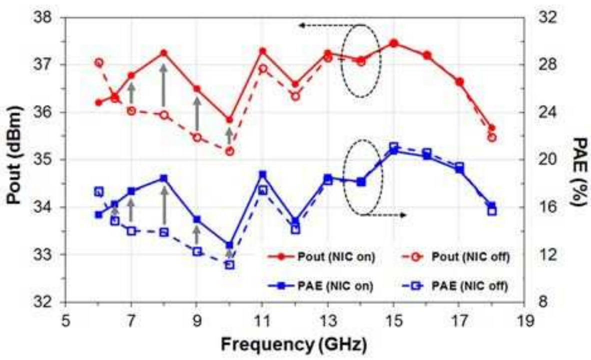


Fig. 7: Measured performance of the proposed PA with and without the NIC.

More meaningful improvement can be observed in the power characteristics (Fig. 7) since NIC-based interstage matching circuit is designed to provide the optimum load impedance to the driver stage in the lower-frequency sub-band. With the NIC, the output power and PAE improves by up to ~ 1.2 dB and ~ 4 %, respectively, between 6 and 11 GHz. For example, at 8 GHz, the output power is increased from 36 to 37.3 dBm and the PAE is improved by 4.5 %. The peak PAE of 13-21 % and the output power of 35.7-37.5 dBm are achieved across the 6-18 GHz frequency bandwidth. The overall PAE degradation due to the power consumption of NIC is estimated to be ~ 1.5 %. Table 1 compares the performance of our PA with the state-of-the-art DA and RMPA using GaN pHEMTs. As the first demonstration of the negative-impedance matched PA (NMPA), the results are

Table I: Performance Comparison Of Gan Broadband Pas

Ref.	Freq (GHz)	Topology	Process	PAE (%)	Pout (W)	Gain (dB)	Area (mm^2)
(6)	2-18	DA	0.25-µm GaN	20-38	9-15	10-14	15.3
(7)	2-20	DA	0.2-µm GaN	15-36	9.9-21.6	N/A	38
(8)	6-18	RMPA	0.25-µm GaN	14-24	3.2-20	17-28	19.25
(9)	6-18	RMPA	0.25-µm GaN	13-25	6-10	18-24	19.8
This work	6-18	NMPA	0.25-µm GaN	13-21	3.7-5.6	13.5-19.1	8.77

promising even though they do not match the best reported power and PAE data. One thing to note is that the overall die size was much smaller than the previous work since NIC implementation was possible in a very small die size, and no lossy matching or feedback was required in our work.

Conclusion:

In this work, a non-Foster matched GaN PA has been developed for multi-octave PA operation. The bandwidth limitation due to high-Q matching has been mitigated through the use of a negative capacitance in the inter-stage matching. Detailed analysis is performed to understand the frequency limitation of NIC approach, which shows that high-frequency limit comes from the self resonance and the low-frequency limit from the power handling capability. Non-Foster matching provides a new perspective in designing broadband PAs.

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