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A Fully Analog Two-way Sequential GaN Power Amplifier with 40% Fractional Bandwidth

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***Abstract* — In this paper, we report a two-way sequential power amplifier (SPA) using GaN HEMTs. The proposed fully analog SPA delivers P_{sat} of approximately 40dBm over 2-3 GHz covering 40% fractional bandwidth. The design consists of a 3dB input coupler, a main amplifier, a peak amplifier, and a 10dB output coupler for power combining. After proper designing and optimizing these critical wideband couplers in terms of both phase and amplitude alignment, the measured final SPA shows 45% to 61% drain efficiency (DE) at 35dBm (5dB backoff) output from 2.1 to 2.9 GHz under CW stimulus. A complete set of SPA with analog RF input and output network is demonstrated.**

***Index Terms* — Sequential power amplifier, broadband, GaN, Efficiency, 4G**

I. Introduction

Efficiently amplifying high PAR (peak-to-average-ratio) modulated signals remains significantly challenging in 4G radio. Advanced radio frequency power amplifier (RFPA) with high peak efficiency including class-E, class-F as well as recent broadband class-J [1] are however limited in average efficiency, which is of greater impact for energy consumption in the transmitter.

Doherty power amplifier (DPA) is a well-known architecture to boost the efficiency at average output power. Unfortunately, DPA's narrowband limitation confines its potential for wideband radio over GHz RF bandwidth. Various researches have been carried out to overcome this fundamental constraint [2]. Nonetheless the reported wideband DPAs have to trade off other RF performance such as gain and/or system complexity.

Sequential power amplifier is one alternative to enhance average efficiency. Its basic concept with key advantages of achieving wideband efficient operation at average power has been introduced in [3]. Advanced SPA concepts have drawn researcher's attention with the development of tunable coupling and asymmetrical configuration in [4] and [5]. Most recently, a wideband SPA using GaN transistors is presented in [6], which is reported to be the first SPA demonstrator. Nevertheless, auxiliary digital signal processor is needed in [6] for maintaining the required phase and amplitude relationships between two feeding signals over wideband, which increased the system complexity and overhead. So far, there is no SPA demonstrator with pure analog implementation owing to the demanding analog signal processing capabilities, especially over GHz bandwidth. In this work, we proposed a fully analog solution utilizing wideband couplers for both RF analog signal splitting and combining as shown in Fig. 1. The paper is organized as follows: Section II providing key design considerations of SPA; measured performances of individual blocks provided in section III, and Section IV showing the characterization of the complete SPA. Conclusion and future work will be given at the end.

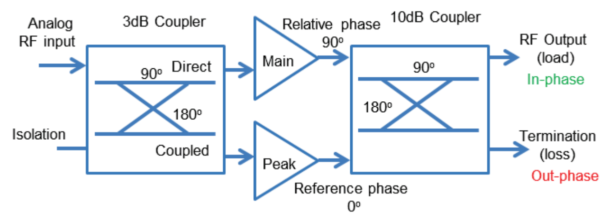


Fig. 1. Schematic of the proposed two-way SPA.

II. Analysis

Unlike active load modulation via impedance inverters (quarter-wavelength lines) in DPAs, wideband coupler is normally used in SPA for combining main and peak amplifier outputs, which is the fundamental operation difference. Adopting the coupler for connection, the main amplifier and peak amplifier are hence isolated and self-contained. No load modulation is occurring in SPA. One of the biggest design challenges here is the wideband coupler to ensure that the voltage waveforms from main and peak amplifiers are arriving in-phase in the desired output port, whereas anti-phase in the loss port over the whole operation frequency. The desired output voltage amplitude at termination port shown in Fig. 1 can be manipulated to be equal but anti-phase to result in a lossless combination at one certain power level. In such a condition, the full power from both main and peak amplifier are ideally delivered to the desired load. In [3], Cripps has derived the lossless condition depending on the voltages and coupling factor:

$$\text{Voltage ratio} = \frac{\text{Vmain}}{\text{Vpeak}} = \sqrt{x-1}$$

where the optimum voltage ratio denotes the ratio between main amplifier output V_{main} and peak amplifier V_{peak}, and x is the coupling factor expressed as a power ratio. Apparently, there will always be power dissipated as loss at non-optimum voltage levels (incomplete voltage cancellation), which is a nature of coupler loss. In practice, the whole SPA design will be dependent on various factors including targeted peak power, gain, PAR, coupling factor, transistor size, and supply voltages as explained in next section. To achieve high average efficiency as a primary goal, targeted average power level of SPA can be arranged close to minimum loss combination zone, scarified with power loss at peak levels. It is known that at peak power level, combination loss will inevitably occur with non-adaptable coupler [4], which could be tolerated to certain extent on account of low probability for high PAR signals in wireless communications. The turn-on point of peak amplifier is basically determined by the class-C bias level as well as input power level, which is similar to DPA.

III. Design

To support broadband efficient operation, the amplifiers and the couplers are designed to cover a frequency range from 2-3 GHz with targeted peak output of 40dBm with 5dB PAR.

A. Main and Peak Amplifiers

Both main and peak amplifiers are designed using commercially 10W packaged GaN HEMTs, and same size transistors were chosen in this design due to availability. Second order low-pass topology is adopted for broadband output matching [2]. Microstrip step impedance transformer is used for input matching. Very similar impedance matching topologies are used in both main and peak amplifiers for the sake of phase alignment. To obtain high average efficiency, peak power delivery (PAR: 5dB) and 10dB gain based on the same size transistors design, bias and supply voltages are carefully chosen in SPA. In our design, the main amplifier is biased at deep Class AB (-2.8V) with low supply of 20V (device recommended voltage V_{dd}: 47V for P_{out} of 10W), which implies main amplifier saturates at lower power than the recommended peak power intentionally, for obtaining high efficiency at average power. Higher supply voltage for peak amplifier is required, because of the significant coupler loss at high power range. It should be noticed that great coupler factor implies tremendous amount of power loss from peak amplifier. The peaking amplifier is biased as Class C (-5V) with supply of 40V to contribute enough power at high power range. 40dBm saturated power were targeted based on this configuration.

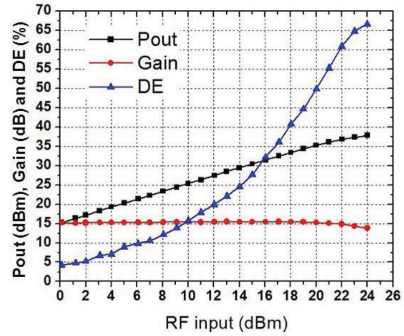
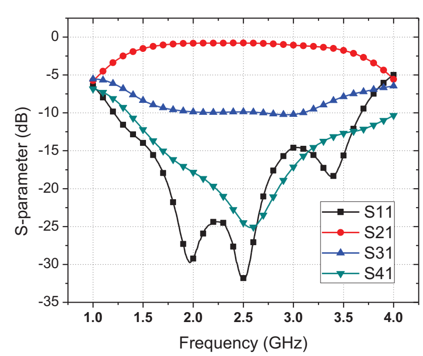


Fig. 2. Measured P_{out}, Gain and DE of the main amplifier (V_{DS} = 20V, V_{GS} = -2.7V, f = 2.5 GHz, CW signal).

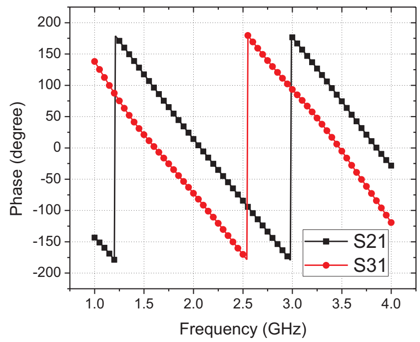
Fig. 2 shows the measured performance of the main amplifier at center frequency 2.5 GHz. P_{1dB} of 38 dBm is obtained with drain efficiency of 65%. The drain efficiency above 55% is obtained from 2~3GHz for the single amplifier design at similar power level (±1dB). With very similar design approach, designed peak amplifier achieves similar broadband performance.

B. Broadband Coupler

The original couplers reported in [7] are adopted for SPA design. The main features of this type of coupler are wideband (>40% fractional BW) and feasible realization of high coupling factor e.g. 10dB. Unlike Lange coupler used in [6], our designed coupler has simplicity of uni-plane (no wire-bonding needed). In addition to the compactness, the two input ports of the designed coupler are located at the same side (shown in Fig. 4), whereas the input ports of Lange coupler are at the opposite side difficult to configure in SPA. Fig. 3(a) and (b) shows the measured performances of fabricated 10dB output coupler. The port definition and connection are shown in Fig. 4. The measurement shows that return loss, directivity, isolation, coupling, phase match (90 degree) are well obtained from 2-3 GHz for the design 10dB coupler. Same approach is used for a coupler with normal coupling factor of 3dB design for power dividing. The input coupling factor is determined by the SPA gain target (~10dB).



(a)



(b)

Fig. 3. Measured (a) S-parameter and (b) phase of the fabricated 10 dB directional coupler (port notation shown in Fig. 4).

IV. SPA Characterization

After verification of the designed sub-modules of SPA, a complete set of proposed fully analog two-way SPA is assembled, as shown in Fig. 4.

Fig. 5 illustrates the measured performance of the whole SPA at center frequency of 2.5 GHz. CW measurement shows that the efficiency at 35dBm P_{out} is approximately 50%, and efficiency drops at higher power levels because of coupler loss. Fig. 6 shows the measured SPA frequency response with CW signal. From 2.1-2.9 GHz, it provides drain efficiency of 45% to 61% at 35 dBm (5dB power backoff from 40dBm peak power), which meets the design target.

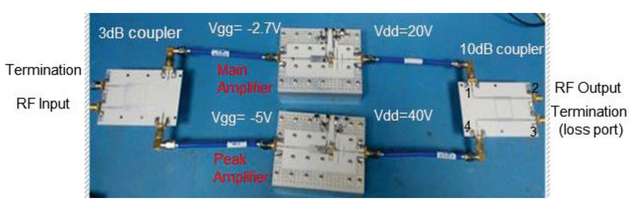


Fig. 4. Assembled two-way SPA (substrate: Roger 4350, h = 0.508 mm, ε_r = 3.66).

V. Conclusion

In this paper, a fully analog single input and single output SPA has been demonstrated. The demonstrator provides 45% to 61% DE at 35 dBm Pout (5dB back-off) from 2.1 to 2.9 GHz. The proposed SPA design has advantage of high efficiency at average power, wideband operation, and simple uni-plane implementation. It shows that the SPA is a promising solution to amplifier wide-band high PAR wireless communication signals. As next step, SPA for even greater PAR signal as well as linearity concern is under development. More advanced architectures of SPA are also under exploration.

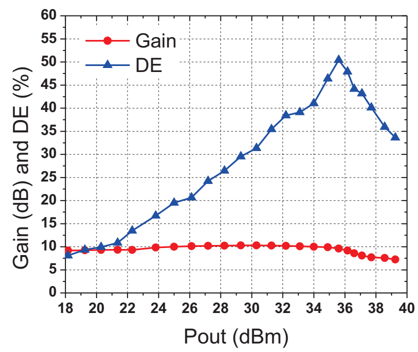


Fig. 5. Measured SPA performance at 2.5 GHz with CW.

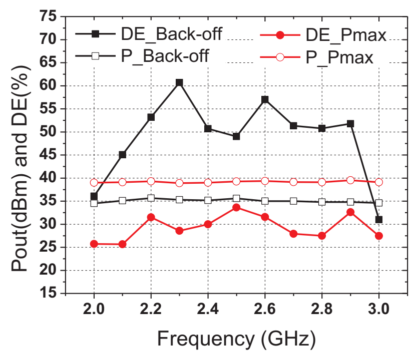


Fig. 6. Measured frequency response of SPA under CW signal at peak and 5dB backoff output power.

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