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Design of Broadband Three-way Sequential Power Amplifiers

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***Abstract*— In this paper, we report a fully analog three-way sequential power amplifiers (SPA) using 10W GaN HEMTs. The proposed three-way SPA delivers P_{sat} of 39~40 dBm over 2.45-2.8 GHz covering a 15.4% fractional bandwidth. The three-way SPA includes a 2:1:1 multi-way splitter, a carrier amplifier, two peaking amplifiers, and a 7:1.5:1.5 combiner for power combining. The measured three-way SPA shows 41% to 44% drain efficiency (DE) at 31 dBm (9 dB backoff) output from 2.5 to 2.8 GHz under CW stimulus. To the best of the authors' knowledge, the proposed three-way SPA is the first time reported three-way SPA in literature.**

***Keywords*— Broadband, Efficiency, GaN, Sequential power amplifier, three-way, two-way, 4G**

I. Introduction

4G wireless communication systems use spectrally efficient modulation schemes to deliver high data rate transmission. These schemes results in the modulated signal with often a high peak-to-average-power-ratio (PAPR) >5dB which therefore puts a significant challenge on the efficient operation of RF power amplifiers in the 4G systems [1].

Doherty power amplifier (DPA) is a well-known architecture to enhance the efficiency at average output power. However, DPA's inherent narrowband limitation confines its potential for wideband radio over GHz RF bandwidth. Various researches have been carried out to overcome this fundamental constraint [2]-[3]. 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 [4]. Advanced SPA concepts have drawn researcher's attention with the development of tunable

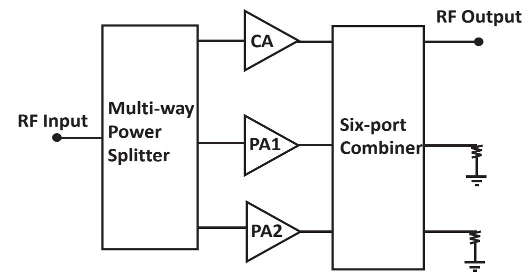

Fig. 1. Schematics of the proposed three-way SPAs.

coupling and asymmetrical configuration in [5] and [6]. Most recently, a wideband SPA using GaN transistors is presented by Merrick *et.al.* in 2014, which is reported to be the first SPA demonstrator [7]. Nevertheless, auxiliary digital signal processor is needed in [7] for maintaining the required phase and amplitude relationships between two feeding signals over wideband, which increased the system complexity and overhead cost.

Similar to the advantages offered by three-way DPA, three-way SPA can further improve the efficiency at a larger power back-off compared with the two-way SPA solution [9], which is desired in advanced wireless communication system such as LTE-A. Due to the phase alignment among three amplifiers, the three-way SPA design is more demanding. Therefore, there is no fully analog three-way SPA demonstrated reported so far, in addition to the multi-way SPA concept proposed in [10].

II. Analysis of the proposed SPAs

Fig. 1 shows the schematics of the designed three-way SPAs. Unlike active load modulation via bandwidth limited impedance inverters (quarter-wavelength lines) in DPAs, wideband coupler is normally used in SPA for

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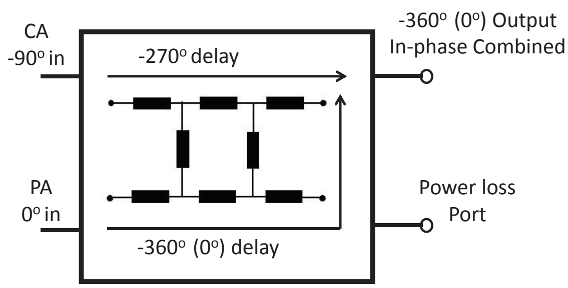


Fig. 2. Schematic of the output coupler of the proposed two-way SPA.

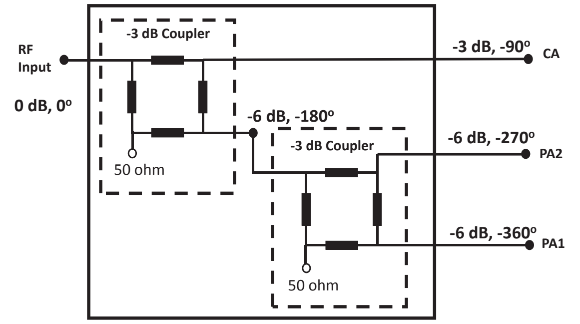


Fig. 3. Schematic of the multi-way splitter of the proposed three-way SPA.

combining carrier and peaking amplifiers' outputs, which is the fundamental operation difference. Adopting the coupler for combining power, the carrier amplifier and peaking 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/combiner to ensure that the voltage waveforms from carrier and peaking amplifiers are arriving in-phase in the desired output port, whereas anti-phase in the loss port over the whole desired operation frequency.

Fig. 3 and Fig. 4 show the schematics of the multi-way splitter and the six-port combiner of the proposed three-way SPA, respectively [10], which is described in the pending U.S. patent application. The multi-way splitter consists of two regular 3dB couplers. The power ratios and the phase information of the carrier, peaking1 and peaking2 are illustrated in Fig. 3.

The six-port combiner has two wide-band 8 dB couplers [8]. The carrier and peaking1 are inputted to the first coupler; the output of the first coupler and the peaking2 are inputted to the second coupler. The two inputted signals of these two couplers require a 90^{o} phase difference as two-way SPA. The required phases of carrier, peaking1 and peaking2 are also shown in Fig. 4. These phase requirements are provided by the multi-way splitter. In other word, the multi-way splitter and the six-port combiner of the proposed three-way SPA are co-deigned to provide a correct phase alignment to meet the phase requirement of a SPA operation.

The turn-on points of two peaking amplifiers are determined by the class-C bias levels as well as input power levels, which are similar to three-way DPA. To be more specific, the peaking1 is biased as a class-C, and the peaking2 is biased as a deeper class-C.

III. Design of the Proposed SPAs

To aim broadband efficient operation, the amplifiers and the splitter/combiner of the three-way SPAs are designed to cover a wide-band with targeted peak output of around 10W.

A. *Carrier and Peaking Amplifiers of the SPAs*

The carrier and peaking amplifiers of the three-way SPAs are designed using Mitsubishi Electric commercially available 10W packaged GaN HEMTs, and same transistors were chosen in this design due to availability. In our design, the carrier amplifier is biased at a deep class-AB (-2.8V) with

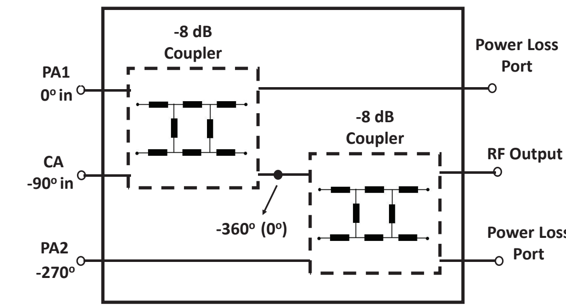


Fig. 4. Schematic of the six-port combiner of the proposed three-way SPA.

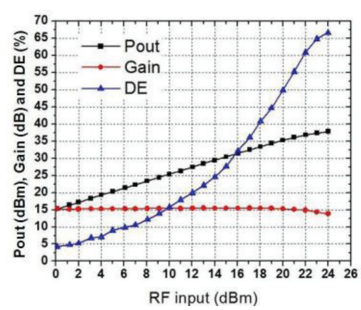


Fig. 5. Measured Pout, Gain, and DE of the carrier amplifier of the three-way SPAs (V_{DS} = 20V, V_{GS} = -2.8V, f = 2.5 GHz, CW stimulus).

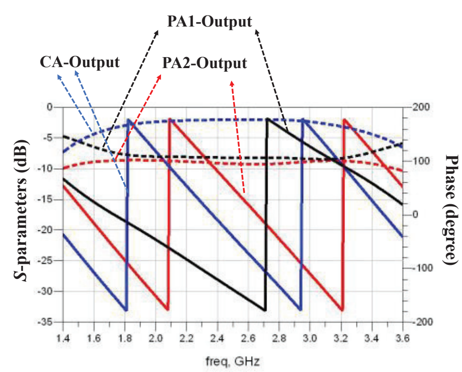
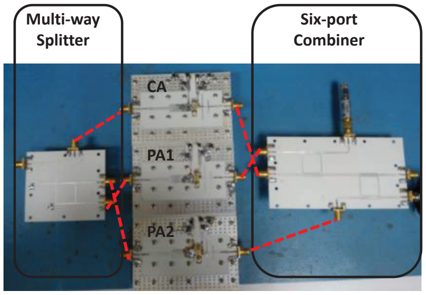


Fig. 6. Measured S-parameter magnitude and phase of the fabricated six-port combiner (7:1.5:1.5) of the three-way SPA.

low supply of 20V (device recommended voltage V_{dd}: 47V for a P_{out} of 10W), and the peaking1 is biased as -5.3V with supply of 25V, and the peaking2 is biased as -7V with supply of 40V. Around 39~40 dBm saturated powers of the three-way



(b)

Fig. 7. Top views of the proposed (a) two-way SPA and (b) three-way SPA.

SPAs were targeted for an straightforward efficiency comparison among single PA and three-way SPA.

Fig. 5 shows the measured performance of the carrier 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 (within ±1dB).

B. *Six-port Combiner*

The original couplers reported in [8] are adopted for SPA design. The carrier features of this type of coupler are wideband (>40% fractional BW) and feasible realization of high coupling factor e.g. 10dB and 8dB. Unlike Lange coupler used in [8], our designed coupler has simplicity of uni-plane (no wire-bonding involved). Fig. 6 shows the measured performances of fabricated six-port combiner (7:1.5:1.5) of the three-way SPA. The port definition and connection are referred in Fig. 2. The measurement shows that directivity, coupling, phase match are well obtained from 2.5-2.9 GHz for the six-port combiner.

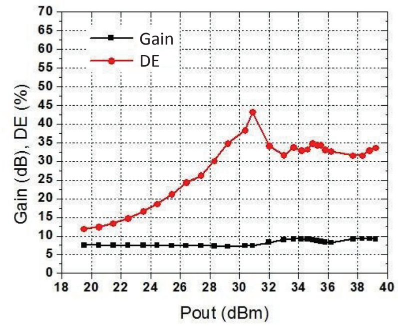
IV. SPA Characterization

After verification of the designed sub-modules of three-way SPA, a three-way SPAs are assembled on RT/Duroid 4350 substrates with 3.66 dielectric constant and 0.508 mm substrate thickness, as shown in Fig. 7.

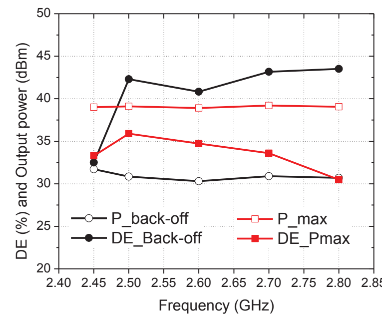
Fig. 8 (a) illustrates the measured performance of the whole three-way SPA at frequency of 2.7 GHz. CW measurement shows that the efficiency at 31dBm power output, corresponding to a 9 dB power back-off, is approximately. Fig. 8 (b) shows the measured three-way SPA frequency response with CW signal. From 2.5-2.8 GHz, it provides drain efficiency of 41% to 44% at 31 dBm, which meets the design target.

V. Conclusions

In this paper, a three-way single- input and single- output SPAs have been demonstrated. The proposed three-way SPA provides 41% to 44% DE at 31 dBm Pout (9dB back-off) from 2.5 to 2.8 GHz. The proposed two SPAs design have 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.



(a)



(b)

Fig. 8. Measured three-way SPA performance of (a) 2.7 GHz with CW and (b) frequency response under CW signal at peak and 9dB backoff output power.

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