Asymmetrical Outphasing: Exploiting Conjugate Continuous Modes of Operation

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***Abstract*—In conventional techniques for efficiency enhancement of outphasing systems, identical power amplifiers are employed for each branch while the output combining network is optimised using reactive compensating elements. In this work a methodology is presented for asymmetrical branch amplifier design based on the conjugate load modulation trajectories seen by each PA branch. Closed form equations and simulations are presented, demonstrating that conjugate modes of operation PAs can be used for the upper and lower amplifier branches in outphasing systems to achieve ideal maximum efficiency over the outphasing back-off range. As a proof of concept, Class B and Class J PAs were built using the Cree CGH40010 GaN HEMT. The Class J PA exhibited a 20% improvement in drain efficiency at 5dB back-off compared to the Class B PA when both were measured with the lower branch outphasing load trajectory.**

***Index Terms*—Power amplifier, Outphasing, Continuous mode, Class B/J**

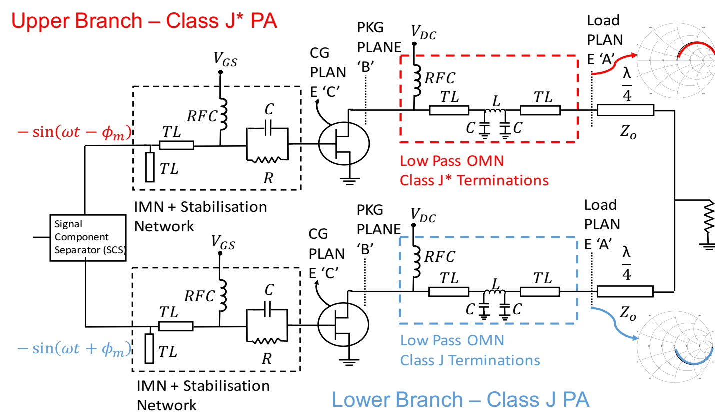

Fig. 1. Asymmetrical outphasing system with conjugate mode design.

I. Introduction

WIRELESS communications is predicted to grow significantly in the next decade thanks to the introduction of smart technologies in wearable, healthcare and vehicular applications. To achieve the necessary increase in capacity, a higher density of base stations is required, resulting in greater energy consumption which efficient amplifiers can help to offset. Single-ended amplifiers cannot operate with sufficient efficiency and linearity when driven by variable time-domain envelope signals with a large Peak-to Average Power Ratio (PAPR). Alternative techniques such as Doherty [1] and outphasing [2] rely on load modulation to increase efficiency over a larger Output Back-Off (OBO). Outphasing is particularly attractive as multiple PA 'branches' are driven with a constant envelope phase-modulated signal and the amplitude modulation is reconstructed by vectorial summation of the output of each branch in the combiner. This is a significant advantage as PAs can theoretically be used in deep saturation without a degradation in the linearity of the transmitted signal. Outphasing has received renewed interest in recent years [3], [4] [5], nevertheless, the reactive loading which each PA branch sees during outphasing operation is a significant obstacle to the method. In conventional PAs, reactive loading degrades efficiency by causing an increased overlap between voltage and current waveforms at the intrinsic plane of the device. Previous attempts to mitigate the problem involved either isolating the two PA branches [6] or compensating for the reactive loading through the design of the combiner itself [2], [7]. Both approaches have limitations in terms of performance, bandwidth and increased complexity.

The approach proposed in this paper is to design each PA so that the outphasing load modulation is transformed, at the Current Generator (CG) plane of each amplifier, to its optimal loading trajectory. This can be achieved without adding any complexity to the system, by operating each branch PA in a conjugate continuous mode and optimising the phase shift introduced by the Output Matching Network (OMN) of each individual amplifier.

II. Theory of Asymmetrical Outphasing

A. Load Modulation at the Intrinsic Device Plane

In an outphasing system with lossless combining, as shown in Fig. 1, the reactive loading taking place at the load plane of the upper and lower branch amplifiers is defined in [8] as:

$$Y_{1,2}(\phi) = R_{load}\frac{2\cos^2\phi}{Z_0^2} \pm jR_{load}\frac{\sin 2\phi}{Z_0^2} \qquad (1)$$

where ϕ is the outphasing angle, related to the OBO by $\beta = 20\log_{10}\left(\cos^2\phi\right)$. Z_0 and R_L are the characteristic impedance of the $\frac{\lambda}{4}$ line and the load impedance indicated in Fig. 1. To evaluate the impact of these trajectories on the efficiency

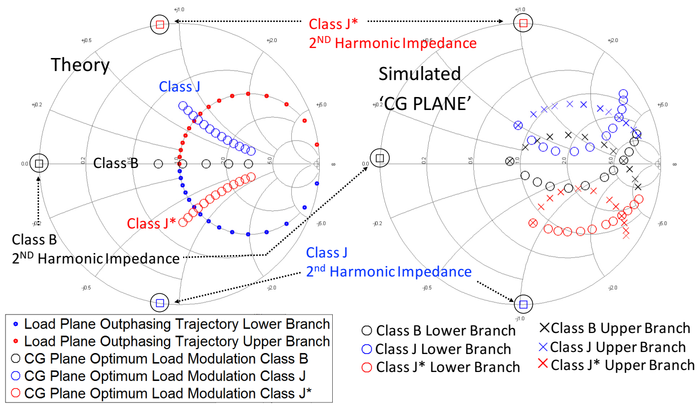

Fig. 2. Ideal outphasing and optimal load modulation trajectories, on the left. On the right, the simulated CG plane impedances for Class B, J and J* PAs with optimal outphasing upper and lower branch loading.

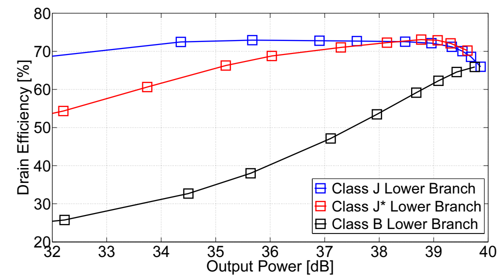

Fig. 3. Simulated efficiency of PAs subject to lower outphasing trajectory.

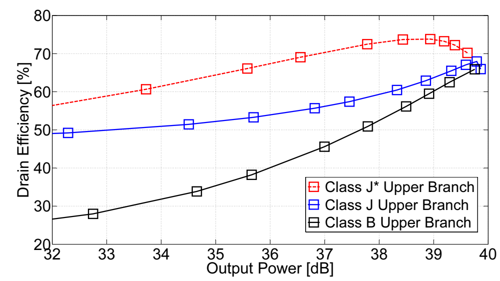

Fig. 4. Simulated efficiency of PAs subject to upper outphasing trajectory.

of the PA it is necessary to determine the load modulation at the intrinsic CG plane of the device which is affected by the OMN and by the device-specific output parasitics. The load modulation trajectory from plane 'A' to the CG plane 'C' in Fig. 1 can be determined as a function of the outphasing angle and the OMN s-parameters, approximating the devices's parasitics as a linear two port network:

$$\Gamma_{PKG}(\phi) = S_{11}^m + \frac{(S_{21}^m)^2 \Gamma_\phi}{1 - S_{22}^m \Gamma_\phi} \qquad (2)$$

$$\Gamma_{CG}(\phi) = S_{11}^p + \frac{(S_{21}^p)^2 \Gamma_{PKG}}{1 - S_{22}^p \Gamma_{PKG}} \qquad (3)$$

where S^p are the the s-parameters of the equivalent output parasitic model, S^m are the s-parameters of the OMN and Γ_ϕ can be determined from the admittance in Eq. 1.

B. Optimal Fundamental Class B/J Load Modulation

The optimal impedances for a given continuous mode of operation can be defined at the CG plane as a function of back-off β and for different values of the continuous design space parameter δ, as previously shown in [9] and [10]. For Class B/J continuous mode PAs the CG fundamental and second harmonic impedances, shown in Fig. 2, are defined as: $Z_{f0} = R_{opt} + j\delta R_{opt}$ and $Z_{2f0} = -j\frac{3\pi}{8}\delta R_{opt}$. Where $\delta \in [-1, 1]$, R_{opt} is the optimal resistance defined as $R_{opt} = 10^{\frac{|\beta|}{20}} R_L$ and R_L is the slope of the ideal Class B loadline $R_L = \frac{2(V_{DC} - V_{knee})}{I_{Max}}$. The reactance of the second harmonic impedance, proportional to R_{opt} and δ, varies as a function of back-off. Moving across the design space it is possible to find a fundamental load modulation trajectory which allows optimal operation with a fixed second harmonic termination. For $\delta \neq 0$ the optimal fundamental load modulation trajectory can be defined as: $Z_{opt} = R_{opt} + j\alpha R_{opt}$, where α is the new design space parameter, determined by the OBO and the initial design space $\alpha = 10^{\frac{\beta}{20}}\delta$. The optimal fundamental load modulation for modes J and J* follows the complex trajectories shown on the left side of Fig. 2. Only for Class B amplifiers with $\delta = 0$ does the optimal fundamental load modulation remain on the real axis.

C. Conjugate Modes of Operation in Outphasing

The outphasing trajectory can be engineered to follow the optimal load modulation for harmonically tuned amplifiers by choosing appropriate values for δ in each branch and optimising the phase shift introduced by each amplifier's OMN. The convexity and concavity of the lower and upper branch load trajectories can be exploited to follow the optimal load modulation profile of conjugate modes of operation. The concave upper branch trajectory favours Class J ($\delta = 1$) optimum fundamental load modulation, while the convex lower branch profile matches the optimal fundamental trajectory of Class J* PAs ($\delta = -1$) as evidenced in Fig. 2. Once the values for δ are chosen, the optimal load modulation trajectory previously introduced as Z_{opt} can be calculated for both branches and set as a target. The S_{11}^m of the OMN of each PA is determined by the mode of operation through the choice of R_L and δ. With knowledge of the devices output parasitics and assuming reciprocal and lossless OMNs, Eq. 3 can be re-arranged so that the argument of S_{21}^m, the phase shift introduced by each OMN, remains as the only unknown. The phase shift is selected to minimise the vectorial distance between $\Gamma_{CG}(\phi)$ and the optimal target impedance trajectory for each branch amplifier.

III. Concept Verification in Simulation

To verify the concept a comparison was made using a simulation test-bed in AWR Microwave Office. The behaviour of Class B, Class J and Class J* PAs was investigated when presented with the outphasing loading. The verified large signal model for the Cree CGH40010 GaN HEMT was used in

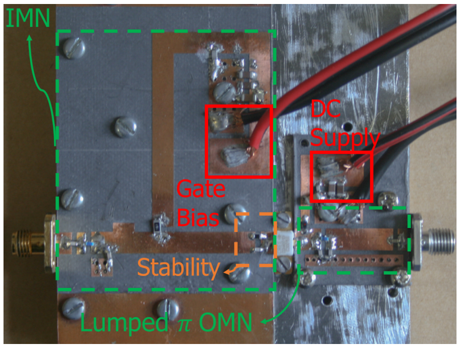

Fig. 5. Photograph of the fabricated PA.

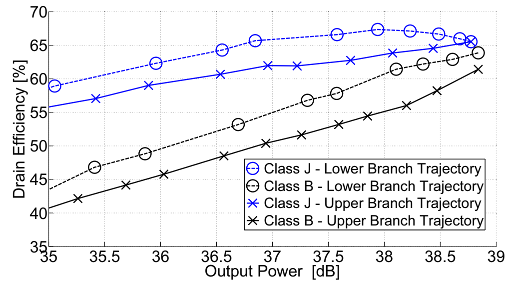

Fig. 6. Measured efficiency of Class B and Class J PAs subject to upper and lower outphasing loading with a constant input power of 28dBm.

the design of all amplifiers. The device was biased with $V_{ds} = 28V$, $I_{dsq} = 13mA$ and stabilised at the input with a series resistor capacitor pair $(2pF||39\Omega)$. An operating frequency of 900MHz and a lumped low-pass π matching topology were chosen for the OMN. The input was conjugate matched for all cases. In order to simulate the effect of the outphasing trajectories at the load plane of each PA, ideal tuners were used and a constant input power of 28dBm was maintained during the load sweep. A variable phase shift was introduced by a series transmission line length at the output of each amplifier and optimised individually for both trajectories, in each PA, to achieve maximum back-off efficiency as described in section II-C. Fig. 2 on the right, illustrates the resulting simulated impedances at the CG plane, while Fig. 3 and Fig. 4 show the drain efficiency of all PAs for both trajectories from harmonic balance simulation. For the Class B PA highest efficiency is obtained by keeping the load modulation as close as possible to the real axis. For Class J and J* PAs the convexity and concavity of the outphasing trajectories are used to follow their respective optimal load modulation. Near to ideal performance is demonstrated for lower and upper branch Class J and J* PAs respectively, over the simulated OBO range.

IV. Experimental Validation on Lower Branch PA

To further validate the proposed method a prototype branch PA was fabricated based on the simulations conducted. The substrate was Duroid 5880 with relative permittivity $\epsilon_r = 2.2$ and thickness 1.57 mm. A photograph of the PA is shown in Fig. 5. A Focus 1880 mechanical load-pull tuner was used to present the outphasing trajectories at the output of each PA, maximising back-off efficiency, and keeping constant input power. Lumped components of the low-pass π OMN were replaced to present the fundamental and second harmonic impedances for Class B and Class J modes of operation, using the same topology. Measured results of the outphasing trajectory sweeps are shown in Fig. 6 for both PAs. Results confirm theory and simulations, with the efficiency of the Class B PA being linearly degraded with increased reactive loading. For the Class J lower branch sweep, a 20% improvement in drain efficiency is obtained, compared to the Class B case. Greater than 55% drain efficiency over 5dB OBO range was measured for a lower branch Class J PA, corresponding to 8dB back-off in the overall outphasing system.

V. Conclusion

The theory of conjugate mode branch design for outphasing has been presented, validated in simulation and experimentally verified on a lower PA branch. Harmonically tuned amplifiers with fundamental reactive loading such as Class J and J* were shown to perform better than conventional Class B PAs as branch amplifiers for outphasing systems. A large difference is also shown in efficiency depending on whether the amplifier is subject to the upper or lower branch load modulation, confirming the advantage of asymmetrical design. This work presents a novel method for the design of load-modulated systems, as the efficiency degradation mechanism is addressed by applying continuous mode PA theory in the branch PA design, without increasing overall complexity.

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