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Publication date	2020-08-06
Publication information	Pang, Jingzhou, Yue Li, Chenhao Chu, Jun Peng, Xin Yu Zhou, and Anding Zhu. "Extend High Efficiency Range of Doherty Power Amplifier by Modifying Characteristic Impedance of Transmission Lines in Load Modulation Network." IEEE, 2020.
Conference details	The International Microwave Symposium (IMS) 2020, Atlanta, Georgia, United States of America, 4-6 August 2020
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/12026
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Publisher's version (DOI)	10.1109/ims30576.2020.9224070

Extend High Efficiency Range of Doherty Power Amplifier by Modifying Characteristic Impedance of Transmission Lines in Load Modulation Network

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***Abstract*— A load modulation network with characteristic impedance-modified transmission lines (TLs) is presented in this paper to extend the efficiency range and bandwidth of the Doherty power amplifier (DPA). Characteristic impedance values for designing the proposed DPA with different high efficiency ranges are given and wideband performance can also be achieved. A DPA with 2.55-3.35 GHz bandwidth using commercial GaN transistors is designed and implemented to validate the proposed architecture. The fabricated DPA achieves a measured 9.2-10.4 dB gain and 44.3-45.4 dBm saturated power. 57.9-75.6% and 47.6-58.8% drain efficiency is achieved at saturation and 8 dB output power back-off (OBO) within the designed bandwidth, respectively. When driven by a 5-carrier 100 MHz OFDM signal with 8 dB peak to average power ratio (PAPR), the proposed DPA achieves adjacent channel leakage ratio (ACLR) of better than -50 dBc after digital pre-distortion with average efficiency of 53.4%, 55.3% and 56.6% at 2.75, 2.95 and 3.15 GHz centre frequencies.**

***Keywords*— Doherty power amplifiers, broadband, extended high efficiency range, load modulation network**

I. Introduction

Doherty power amplifier (DPA) is an effective architecture to improve the back-off efficiency performance, which makes it suitable for modern wireless communication systems adopting modulated signals with high peak to average power ratio (PAPR). Conventional DPAs usually provide 6 dB high efficiency range. However, modulated signals with 8-12 dB PAPR are widely deployed in wireless systems today. In the upcoming 5G era, the output power of the PAs may need to be adjusted according to the data traffic. Meanwhile, 5G systems employs more new frequency bands and the signal bandwidth will also be greatly increased. This leads that the PAPR of the transmit signals may become even higher. It is thus desirable for DPAs to provide high efficiency performance at a large power range across wide bandwidth.

Recently, by introducing techniques such as post-matching[1] and continuous mode operation[2], the bandwidth of DPAs has been greatly extended. However, the above bandwidth extension techniques mostly target at 6 dB output power back-off (OBO). Employing asymmetrical configuration [3] or multiple device [4] architectures can extend the efficiency range of DPAs, while the bandwidth extension technique might not be applicable at the same time and the design method becomes more complex. Therefore,

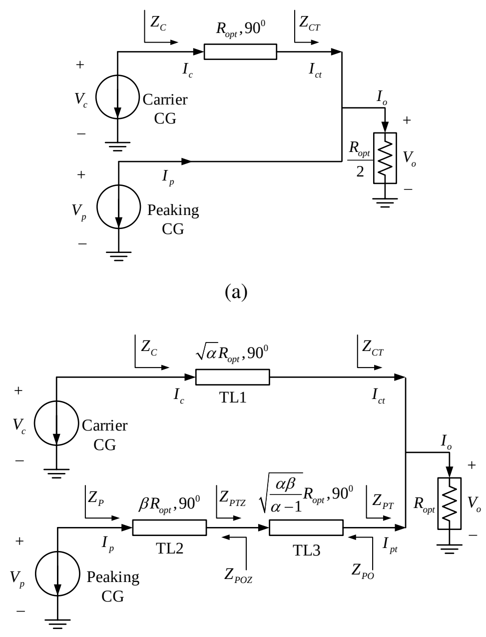

Fig. 1. Theoretical block diagrams of: (a) conventional DPA, (b) proposed DPA.

it is very attractive to explore modified DPA architectures with both extended high efficiency range and wideband performance.

In this paper, a modified DPA architecture is presented with transmission line (TL)-based load modulation network. It is illustrated that, by setting different characteristic impedance for the employed TLs, the high efficiency range of the proposed DPA can be extended to different OBO levels and the bandwidth performance can also be improved due to the achieved impedance. A wideband DPA with 2.55-3.35 GHz bandwidth is designed and implemented using equal-cell transistors. The fabricated DPA presents excellent efficiency performance at 8 dB OBO within the designed bandwidth.

II. Proposed Modified DPA With Extended High Efficiency Range and Wideband Performance

Fig. 1(a) presents the theoretical block diagram of the conventional DPA. A quarter-wave length TL with

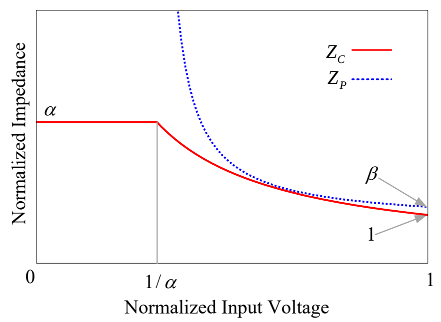

Fig. 2. Normalized impedance of the carrier of peaking branch.

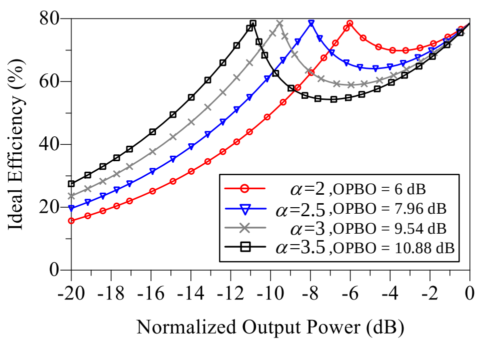

Fig. 3. Ideal efficiency performance of the proposed DPA for different value of α.

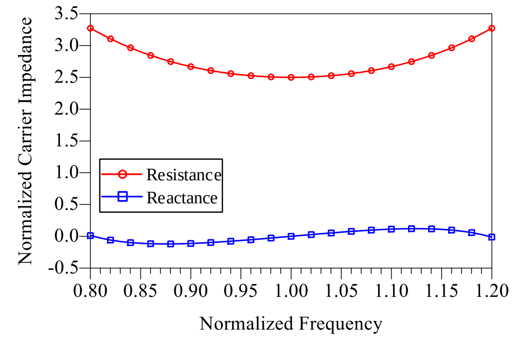

Fig. 4. Normalized carrier back-off impedance.

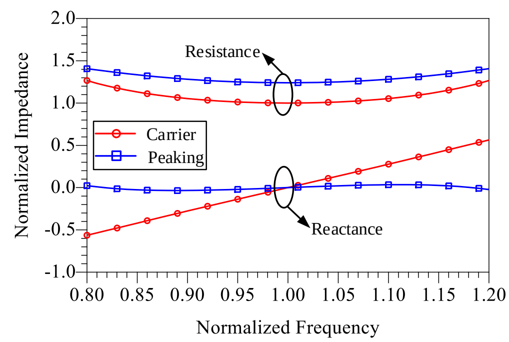

Fig. 5. Normalized carrier and peaking impedance at saturation.

characteristic impedance of R_{opt} is employed as the load modulation network (LMN) to achieve 6 dB high efficiency range. The combining load is set to $R_{opt}/2$. To extend the high efficiency range and the bandwidth, a DPA architecture using an LMN with characteristic impedance-modified TLs is presented here as shown in Fig. 1(b). The proposed LMN consists of three quarter wavelength TLs with characteristic impedance of $\sqrt{\alpha}R_{opt}$, $\sqrt{\frac{\alpha\beta}{\alpha-1}}R_{opt}$ and βR_{opt}. R_{opt} is the optimal impedance for the carrier device and the combining load is set to R_{opt}. By setting different values of α, the proposed architecture can achieve different high efficiency ranges. The parameter β represents the ratio between the peaking and carrier optimal impedance. β gives more freedom to choose different value of the peaking active device. The current generators (CGs) are used to represent the function of the carrier and peaking actice devices. To run the Doherty operation, the magnitude of carrier and peaking current can be expressed as,

$$|I_c| = |v_{in}| \ , \ 0 \leq |v_{in}| \leq 1 \tag{1}$$

$$|I_p| = \begin{cases} 0 & ,0 \leq |v_{in}| \leq 1/\alpha \\ \dfrac{\alpha}{\sqrt{(\alpha-1)\beta}}|v_{in}| - \dfrac{1}{\sqrt{(\alpha-1)\beta}} & ,1/\alpha < |v_{in}| \leq 1 \end{cases} \tag{2}$$

where I_c and I_p are the normalized currents of the carrier and peaking CGs, v_{in} is the normalized input voltage. α represents the threshold when the peaking device turns on. It should be noticed that the maximum value of I_p is $\sqrt{(\alpha-1)/\beta}$.

In this configuration, the LMN at the carrier and peaking CG planes can be calculated or simulated using the network feature at the centre frequency. The normalized impedance at the carrier and peaking CG planes is shown in Fig. 2. At OBO, the carrier impedance is αR_{opt} which can provide high back-off efficiency. At saturation, the carrier and peaking impedance becomes 1 and β due to the load modulation, respectively. Therefore, the output voltage at the peaking CG should be $\sqrt{(\alpha-1)\beta}$. Assume the carrier and peaking PAs are both operated in class B mode, based on the load modulation process, we can obtain the efficiency performance of the proposed DPA. Fig. 3 shows efficiency of the proposed DPA for different value of α. It can be seen that, when the value of α changes from 2 to 3.5, the high efficiency range of the proposed DPA changes from 6 dB to 10.88 dB. Meanwhile, the optimal impedance of the peaking device can be adjusted with different value of β, which gives us more freedom for the peaking PA design.

In this design, $\alpha = 2.5$ is firstly chosen to achieve about 8 dB high efficiency range. In order to use same devices for both carrier and peaking PAs, the maximum value of I_p should be set close to the maximum value of I_p. Meanwhile, to avoid much higher peaking drain supply voltage, the value of β should not be so large. Consider these two conditions, $\beta = 1.24$ is chosen in the design. In this configuration, the maximum peaking current is 1.09 times larger than the carrier one, the drain supply voltage of the peaking PA is 1.36 times larger than the carrier PA. Fig. 4 presents the normalized carrier impedance at OBO in this configuration, the

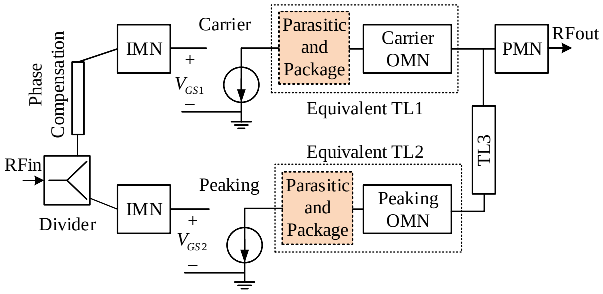

Fig. 6. Schematic of the designed DPA.

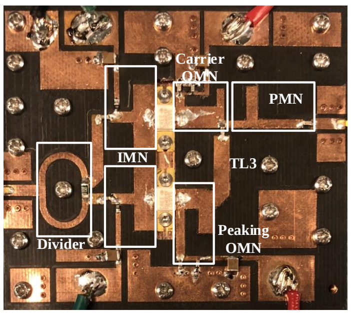

Fig. 7. Photograph of the fabricated DPA.

reference is R_{opt}. Consider both the resistance and reactance, the carrier back-off impedance is close to the target value within the presented 40% fractional bandwidth in Fig. 4. The phase difference between the carrier and peaking CGs will affect the load modulation. Assume we use a simple quarter wavelength TL to compensate the phase difference, then we have the following relationship,

$$I_c = I_p \cdot e^{j(\pi f/2)} \tag{3}$$

Where f is the operation frequency. In this situation we can obtain the carrier and peaking impedance versus frequency at saturation, which is shown in Fig. 5. Compared with the peaking branch, the mismatch of the carrier impedance is more obvious. The mismatch might decrease performance of the proposed DPA to some extent at saturation when the operation frequency deviates from the center. Nevertheless, this mismatch mainly exists in the carrier PA and its impact on performance will be limited.

In practical designs, the active devices can not be used as ideal CGs, the parasitic and package parameters must be considered in the LMN. Therefore, the entire architecture of the proposed DPA should be adjusted, as shown in Fig. 6. The carrier and peaking output matching networks (OMNs) are considered as part of equivalent TLs, which absorb the parasitic and package components of the employed transistors. A post matching network (PMN) which match the combining load R_{opt} to 50 Ω output load is added. A power divider is employed to separate the input signal and a 50 Ω quarter wavelength TL is added in front of the carrier input matching network (IMN) to provide the required combining phase.

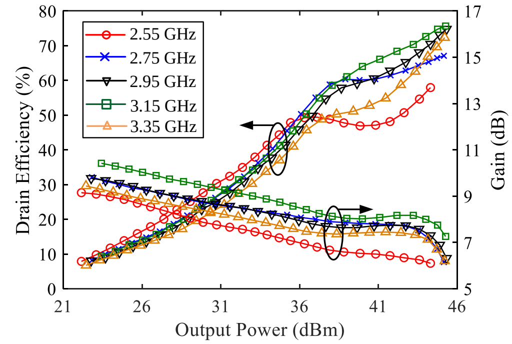

Fig. 8. Measured drain efficiency and gain versus the output power from 2.55 GHz to 3.35 GHz.

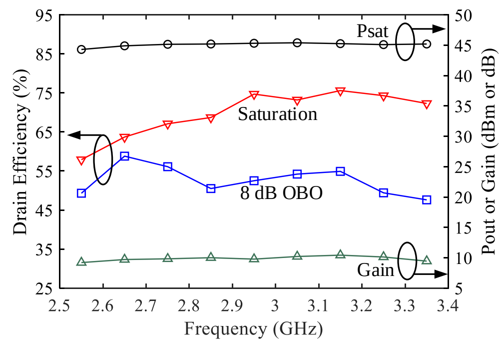

Fig. 9. Measured drain efficiency, output power and gain versus frequency from 2.55 GHz to 3.35 GHz.

III. PA Implementation and Measurement Results

The photograph of the fabricated DPA is shown in Fig. 7, the related circuits structure are marked in this figure. The design is implemented using commercial GaN HEMTs CGH40010F from Wolfspeed for both carrier and peaking PAs on a 31 mil Rogers 5880 substrate with the size of 74.5 mm$\times$66.8 mm. During all the following measurements, the fabricated DPA was biased with carrier quiescent current of 90 mA and peaking gate voltage of -6.4 V. Based on the configuration of $\alpha = 2.5$ and $\beta = 1.24$, the drain supply voltages of the carrier and peaking PAs were set to 26 V and 34 V. In this configuration, R_{opt} is set to 32 Ω and the required impedance of the peaking device at saturation should be βR_{opt}, which is about 40 Ω. R_{opt} and βR_{opt} are the characteristic impedance of the equivalent TL1 and TL2. The carrier and peaking OMNs employ similar TL structures as shown in Fig. 7. The PMN is a T-shaped TL structure which matches the 50 Ω load to 32 Ω in the designed band. The IMNs employs the stepped-TL structure and a large resistance is added in the gate bias line to provide wideband RF open feature. A simple Wilkinson divider is employed to separate the input signal.

A. Continuous-Wave (CW) Signal Measurements

The implemented DPA was firstly measured using CW signal from 2.55 GHz to 3.35 GHz with the step of 0.1 GHz. Fig. 8 presents the measured drain efficiency and gain versus

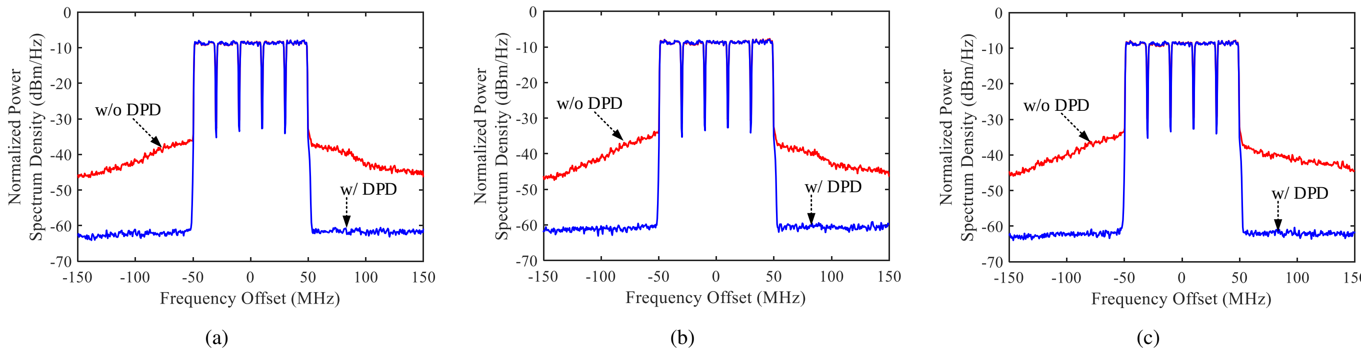

Fig. 10. Output spectrum with and without DPD under stimulation of a 5-carrier 100 MHz OFDM signal with 8 dB PAPR at: (a)2.75 GHz, (b) 2.95 GHz and (c) 3.15 GHz.

Table 1. Performance Comparison.

Ref. (Year)	Freq (GHz)	Pout (dBm)	OBO (dB)	η_{sat} (%)	η_{bo} (%)
[2]2018	3.3-3.75	48-48.8	8	58-71	44-55
[3]2018	1.35-2.05	41.5-42.4	9	65-75	52-55
[4]2019	1.6-2.6	45.5-46	9.5	53-66	50-53
[6]2019	2.55-3.8	48.8-49.8	8	54-67	47-60
[7]2018	1.7-2.5	48-48.9	8	48-58*	43-53*
This Work	2.55-3.35	44.3-45.4	8	57.9-75.6	47.6-58.8

* - Power added efficiency

the output power at some of the measured frequencies. It can be seen that obvious Doherty operation was achieved by implemented PA within the designed band. To better present the wideband performance of the proposed DPA, the drain efficiency at saturation and 8 dB OBO, small signal gain and the saturated output power versus frequency are given in Fig. 9. The implemented DPA achieves 57.9% to 75.6% peaking efficiency with 44.3 to 45.4 dBm saturated output power and 9.2 to 10.4 dB small signal gain throughout the measured frequency band. Meanwhile, back-off efficiency of 47.6%-58.8% is obtained at 8 dB OBO.

B. *Modulated Signal Measurements*

To evaluate the performance of the proposed DPA in actual wireless communication systems, a 5-carrier 100 MHz bandwidth OFDM signal with 8 dB PAPR was employed to perform the measurement. Iterative learning control-based DPD [5] was then performed to correct the nonlinearity. Fig. 10 presents the output spectrum at 2.75 GHz, 2.95 GHz and 3.15 GHz with and without DPD. It can be seen that excellent linearity can be achieved after DPD. The measured average output power is around 37 dBm and the average efficiency achieves 53.4%, 55.3% and 56.6%. The ACLR is better than -26.5 dBc without DPD and improved to better than -51.5 dBc after DPD performed.

Table 1 summarizes the performance of some recently published wideband high efficiency PAs. η_{sat} and η_{bo} represent the drain efficiency at saturation and back-off, respectively. It can be seen that the proposed DPA achieves excellent efficiency performance with comparable bandwidth.

IV. Conclusion

A DPA architecture with modified LMN is presented in this paper. By employing the TL based LMN, the proposed DPA architecture provides both extended efficiency range and wideband performance. Higher than 47.6% drain efficiency was achieved at 8 dB OBO throughout a 800 MHz band. When driven by a 5-carrier 100 MHz OFDM signal, better than -50 dBc ACPR was achieved after DPD with higher than 50% average efficiency at 2.75, 2.95 and 3.15 GHz.

Acknowledgment

This work was funded by Science Foundation Ireland under Grant Numbers 13/RC/2077, 17/NSFC/4850 and 16/IA/4449.

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