LETTER

Highly efficient and broadband continuous Doherty power amplifier using modified harmonic matching structure

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Abstract A highly efficient and broadband continuous Doherty power amplifier (DPA) using modified harmonic matching structure is proposed in this paper. The proposed structure can match the fundamental and harmonic impedance of the carrier power amplifier and peaking power amplifier (PA) precisely. To verify this structure, A highly efficient and broadband Doherty power amplifier based on this structure is designed and fabricated using a CGH40010F GaN HEMT packaged device. The measurement results illustrate that drain efficiency (DE) of 68.1%–72.1% at the saturated output power (Pout) and 48.4%–63.5% at 6 dB output back-off (OBO) is achieved across the band 1.6–2.1 GHz with the saturated output power is about 43.2–44.5 dBm.

Keywords: highly efficient, broadband, continuous, Doherty power amplifier, harmonic matching

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Due to the increasing demand of high-speed data transmission, the modulated signal with high peak to average power ratio has been widely used in the wireless communication. The DPA, which can achieve high efficiency at the OBO level, has been widely researched [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. The diversity of modern communication standard requires that the DPA has an extended OBO range and enhanced bandwidth with high efficiency.

So far many methods have been proposed to expand bandwidth and improve efficiency for the DPA. In the paper [18], the author analyses the frequency response of the conventional DPA and expands the bandwidth by reducing impedance transformation ratio of \(\lambda/4\) impedance inverter. In the paper [19], the author adds a \(\lambda/4\) shunt short stub into the combining network in order to get the complex load impedance which can maintain the proper load modulation in a wider bandwidth. In the paper [20], the non-infinite peaking impedance at the OBO level is used to enhance the performance of broadband DPA. In the paper [21], the non-infinite peaking impedance and the complex load impedance are combined for broadband operation of the DPA. Nevertheless, these methods only aim to optimize the fundamental impedance, with the harmonic impedance ignored.

The continuous mode proposed by S.C. Cripps [26], which has a series of resistive-reactive fundamental and purely reactive second harmonic terminations, can maintain the same efficiency performance as class-B mode. Therefore, it is a suitable solution to realize a broadband PA. In the paper [22], the post harmonic tuning network is used to optimize the combining harmonic load impedance for efficiency and bandwidth enhancement in the entire OBO region. In the paper [23], the harmonic suppressing and matching circuit is added into the output matching network of the carrier PA and peaking PA to realize a broadband continuous DPA. These results illustrate that the introduction of harmonic tuning or matching network can improve the efficiency performance of the broadband DPA.

However, the fundamental matching, especially in the impedance inverter network, will be affected by the extra harmonic matching circuit [22, 23], which increases the design difficulty greatly. In this paper, a modified harmonic matching structure for the continuous DPA is proposed. The methodology of realizing a continuous DPA is presented in detail. A highly efficient and broadband continuous DPA is designed, fabricated and measured to verify the proposed structure.

2. Modified structure of continuous DPA

Fig. 1 shows the simplified circuit of the conventional DPA, in which each transistor is assumed to be an ideal current generator. The carrier impedance inverter network (CIIN) and the peaking output matching network (POMN) are used for impedance transformation. \(Z_{L1}\) represents the combining fundamental load impedance, which is always transformed from a load of 50 Ohm by the post matching network (PMN). Based on the active load modulation, the effective fundamental load impedance \(Z_{C1}'\) and \(Z_{P1}'\) of the carrier PA and peaking PA are given as follows:

\[
Z_{C1}' = Z_{L1} \left( 1 + \frac{I_{P1}'}{I_{C1}'} \right) \tag{1}
\]

\[
Z_{P1}' = Z_{L1} \left( 1 + \frac{I_{C1}'}{I_{P1}'} \right) \tag{2}
\]

where \(I_{C1}'\) and \(I_{P1}'\) are in-phase fundamental currents of the carrier PA and peaking PA. When the input power increases, the peaking PA starts to work and \(Z_{C1}'\) increases along with \(I_{P1}'/I_{C1}'\). Owe to the impedance transformation of the CIIN, The optimal fundamental impedance of the carrier PA \(Z_{C1}\) decreases, which keeps the drain voltage of the carrier
PA saturated constantly. Therefore, high efficiency can be acquired in the entire OBO region.

Fig. 2 shows the structure of the proposed continuous DPA. The CIIN keeps invariant so that the carrier harmonic current can pass through it. The combining of the peaking harmonic suppressing and matching network (PHSMN) and the peaking fundamental tuning network (PFTN) behaves as the POMN. The combining of the carrier harmonic matching network (CHMN) and the post matching tuning network (PMTN) behaves as the PMN.

The optimal fundamental and second harmonic impedance of the peaking PA \( Z_{P1} \), \( Z_{P2} \) (the third harmonic impedance is not considered in this analysis) can easily be matched under the effective fundamental load impedance of the peaking PA \( Z_{P1}' \) by the PHSMN and PFTN like a single-stage continuous PA, because they only need be matched optimally at the saturated output power. However, the PHSMN must be designed strictly to get a purely reactive second harmonic impedance to prevent the second harmonic current flowing into the combining point. An offset line is added behind the POMN to get an infinite peaking backward fundamental impedance \( Z_{PB1} \) at the low Pout. In practice, only the \( Z_{PB1} \) at the center frequency is infinite [20], which shifts from the open circuit when the frequency shifts from the center frequency. Therefore, it must be considered in the fundamental matching.

The CIIN can easily be designed under the effective fundamental load impedance of carrier PA \( Z_{C1}' \) and non-infinite peaking backward fundamental impedance \( Z_{PB1} \) to get an optimal fundamental impedance of the carrier PA \( Z_{C1} \) at the saturated output power and OBO level like a conventional DPA. Suppose that the transmission matrix of the designed CIIN is

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]

the optimal second harmonic impedance of the carrier PA \( Z_{C2} \) can be obtained by the following equation:

\[
Z_{C2} = \frac{Z_{C2}'A + B}{Z_{C2}'C + D}
\]

where \( Z_{C2}' \) represents the effective second harmonic load impedance of the carrier PA. According to equation (4), it is concluded that even if the CIIN has been designed, the optimal second harmonic impedance of the carrier PA can also be matched by setting proper value of \( Z_{C2}' \).

Owe to the harmonic suppressing in the POMN, it is easy to get that \( I_{P2}' = 0 \) and \( I_{C2}' \neq 0 \), where \( I_{P2}' \) and \( I_{C2}' \) are second harmonic currents of the peaking PA and carrier PA. The effective second harmonic load impedance of the carrier PA \( Z_{C2}' \) is given as follows:

\[
Z_{C2} = Z_{L2}\left(1 + \frac{I_{P2}'}{I_{C2}'}\right) = Z_{L2}
\]

where \( Z_{L2} \) represents the combining second harmonic load impedance. It can be seen that the effect of load modulation on the effective second harmonic load impedance of the carrier PA \( Z_{C2}' \) is eliminated. With regard to effect on \( Z_{C2}' \), the POMN with the offset line can be equivalent as a shunt short stub in the entire OBO region, because the suppressing of the second harmonic by the POMN makes the peak backward second harmonic impedance \( Z_{PB2} \) purely reactive. As a result, \( Z_{C2}' \) should be modified by

\[
Z_{C2}' = \frac{Z_{PB2}}{Z_{L2} + Z_{PB2}}
\]

The \( Z_{PB2} \) is fixed once the POMN and offset line is completed. Therefore, the combining second harmonic load impedance \( Z_{L2} \) determines the value of \( Z_{C2}' \). By the transformation of equation (6), we can get the value of target combining second harmonic load impedance \( Z_{L2} \):

\[
Z_{L2} = \frac{Z_{PB2} \cdot Z_{C2}'}{Z_{PB2} + Z_{C2}'}
\]

The target combining second harmonic load impedance \( Z_{L2} \) can easily be matched by the CHMN, after which PMTN is designed to match the combining fundamental load impedance \( Z_{L1} \).

Finally, the fundamental and the second harmonic impedance of the continuous DPA can be well matched based on the above design methodology. When the third harmonic is considered, the continuous mode like continuous class-F [27, 28] and continuous class-F\(^{-1} \) [29, 30] can be used for a greater efficiency enhancement.

3. Continuous DPA design

In order to verify the proposed structure, a highly efficient broadband continuous DPA based on this structure is designed, using a CGH40010F 10W GaN HEMT packaged device. The drain bias voltage is 28 V and the gate bias voltages of the carrier PA and peaking PA are −3 V and −6 V respectively. The DPA is fabricated on substrate Rogers
4350B with a dielectric constant of 3.66 and a thickness of 0.762 mm.

Load-pull simulation system is applied to get the optimal fundamental and second harmonic impedance at the package plane. Fig. 3 shows the optimal fundamental and second harmonic impedance regions of the carrier PA and peaking PA at 1.7 GHz and 2.0 GHz.

The combining fundamental load impedance $Z_{C1}$ is set to 25 Ohm, which is a conventional DPA configuration so the effective fundamental load impedance $Z_{C1}'$ and $Z_{P1}'$ of the carrier and peaking PA at the saturated output power is 50 Ohm. Based on this configuration and the load-pull result, the PHSMN and PFTN are designed, as shown in Fig. 4. Fig. 5 shows the simulation result of the fundamental and second harmonic impedance of the peaking PA at the package plane, where the fundamental frequency is from 1.6 GHz to 2.1 GHz. It can be observed that the harmonic impedance is in the margin of the Smith chart which can be regarded as a proper matching. The offset line is added to get an appropriate peaking backward fundamental impedance $Z_{PB1}$ at the OBO level. Fig. 6 shows the peaking backward fundamental impedance $Z_{PB1}$ and the peaking backward second harmonic impedance $Z_{PB2}$ of the designed POMN with the offset line.

The CIIN is designed under the effective fundamental load impedance $Z_{C1}'$ (50 Ohm at the saturated output power and 25 Ohm at 6 dB OBO) and non-infinite peaking backward fundamental impedance $Z_{PB1}$ (at 6 dB OBO), as shown in Fig. 7. Fig. 8 shows the simulation result of the fundamental impedance of the carrier PA. It can be seen that desired fundamental matching is achieved at both the saturated output power and 6 dB OBO.

According to the load-pull result of the optimal second harmonic impedance $Z_{C2}$ and simulated peaking backward second impedance $Z_{PB2}$, the design space of combining second harmonic load impedance $Z_{L2}$ can be obtained, as shown in Fig. 9. Based on the design space of the combining second harmonic load impedance $Z_{L2}$, the CHMN is designed and then the PMTN is designed to match the combining fundamental load impedance of 25 Ohm, as shown in Fig. 10. Fig. 11 shows the combining fundamental and second harmonic load impedance of the designed PMN. It can be seen that the second harmonic impedance is well matched and
the fundamental impedance slightly shifts from but can be approximated as 25 Ohm. The second harmonic impedance of carrier PA $Z_{C2}$ is also simulated, as shown in Fig. 8. It can be seen that $Z_{C2}$ is well matched in the optimal impedance region.

With the POMN, CIIN and PMN synthesized, the completed continuous DPA is designed and fabricated, as shown in Fig. 12.

4. Simulation and measurement results

Fig. 13 show the simulation result of voltage and current waveform of the carrier PA at the intrinsic current generator plane at 1.85 GHz. It can be seen that the waveform is similar to that of continuous class-$F^{-1}$ mode.

The fabricated continuous DPA is measured under the continuous wave signal stimulation. Fig. 14 gives the measured drain efficiency and gain of the fabricated DPA versus output power. The measurement results illustrate that the DE is about 68.1%–72.1% at the saturated output power and 48.4%–63.5% at 6 dB OBO is achieved with a saturated output power about 43.2–44.5 dBm and gain about 9.5–10.8 dB over the frequency range from 1.6 GHz to 2.1 GHz, as shown in Fig. 15. Table I outlines the comparison between the current work and some previous state-of-the-art DPA results.

The fabricated continuous DPA is also measured under the modulated signal stimulation to access the efficiency and linearity performance. 20 MHz LTE signal with 7.5 dB
PAPR is applied to this DPA. As is shown in Fig. 16, the average DE is about 44.7%–54.2% with an average output power from 35.9 dBm to 36.7 dBm from 1.6 GHz to 2.1 GHz and the adjacent channel power ratio (ACPR) is between −25.6 dBc and −23.6 dBc over the entire band.

5. Conclusion

In this paper, a broadband continuous Doherty power amplifier using modified harmonic matching structure is proposed. The measured DE is about 68.1%–72.1% at the saturated Pout, 48.4%–63.5% at 6 dB OBO. The saturated output power is about 43.2–44.5 dBm across the band 1.6–2.1 GHz. According to the measurement results, the continuous DPA designed by this structure can greatly increase the efficiency compared with the conventional DPA.

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References

[1] W.H. Doherty: “A new high efficiency power amplifier for modulated waves,” Proc. IRE 24 (1936) 1163 (DOI: 10.1109/JRPROC.1936.228468).
[2] M. Iwamoto, et al.: “An extended Doherty amplifier with high efficiency over a wide power range,” IEEE Trans. Microw. Theory Techn. 49 (2001) 2472 (DOI: 10.1109/22.971638).
[3] X.H. Fang, et al.: “Extension of high-efficiency range of Doherty amplifier by using complex combining load,” IEEE Trans. Microw. Theory Techn. 62 (2014) 2038 (DOI: 10.1109/TMTT.2014.2333713).
[4] J. Xia, et al.: “High-efficiency GaN Doherty power amplifier for 100-MHz LTE-advanced application based on modified load modulation network,” IEEE Trans. Microw. Theory Techn. 61 (2013) 2911 (DOI: 10.1109/TMTT.2013.2269052).
[5] J.H. Qureshi, et al.: “A wide-band 20 W LMMOS Doherty power amplifier,” IEEE MTT-S Int. Microw. Symp. Dig. (2010) 1504 (DOI: 10.1109/MWSYM.2010.5517561).
[6] X. Chen and W. Chen: “A novel broadband Doherty power amplifier with post-matching structure,” Proc. Asia–Pacific Microw. Conf. (2012) 370 (DOI: 10.1109/APMC.2012.6421601).
[7] V. Camarchia, et al.: “A design strategy for AM/PM compensation in GaN Doherty power amplifiers,” IEEE Access 5 (2017) 22244 (DOI: 10.1109/ACCESS.2017.2759164).
[8] A. Barthwal, et al.: “Bandwidth enhancement of three-stage Doherty power amplifier using symmetric devices,” IEEE Trans. Microw. Theory Techn. 63 (2015) 2399 (DOI: 10.1109/TMTT.2014.2452255).
[9] D. Gustafsson, et al.: “A modified Doherty power amplifier with extended bandwidth and reconfigurable efficiency,” IEEE Trans. Microw. Theory Techn. 61 (2013) 533 (DOI: 10.1109/TMTT.2012.2227783).
[10] D.Y.-Y. Wu, et al.: “A mixed-technology asymmetrically biased extended and reconfigurable Doherty amplifier with improved power utilization factor,” IEEE Trans. Microw. Theory Techn. 61 (2013) 1946 (DOI: 10.1109/TMTT.2013.2252188).
[11] J. Fang, et al.: “Design of a post-matching asymmetric Doherty power amplifier for broadband applications,” IEEE Microw. Wireless Compon. Lett. 26 (2015) 52 (DOI: 10.1109/LMWC.2015.2505651).
[12] J. Fang, et al.: “A post-matching Doherty power amplifier employing low-order impedance inverters for broadband applications,” IEEE Trans. Microw. Theory Techn. 63 (2015) 4061 (DOI: 10.1109/TMTT.2015.2495201).
[13] H. Golestan, et al.: “An extended bandwidth three-way Doherty power amplifier,” IEEE Trans. Microw. Theory Techn. 61 (2013) 3318 (DOI: 10.1109/TMTT.2013.2275311).
[14] X. Fang, et al.: “Broadband, wide efficiency range, Doherty amplifier design using frequency-varying complex combining load,” IEEE MTT-S Int. Microw. Symp. Dig. (2015) 1 (DOI: 10.1109/MWSYM.2015.7166785).
[15] R. Giorfla, et al.: “A design approach to maximize the efficiency vs. linearity trade-off in fixed and modulated load GaN power amplifiers,” IEEE Access 6 (2018) 9247 (DOI: 10.1109/ACCESS.2018.2807479).
[16] T. Qi, et al.: “Canceling intermodulation products: A high-efficiency and linear-asymmetric Doherty PA,” IEEE Microw. Mag. 20 (2019) 98 (DOI: 10.1109/MMM.2018.2875613).
[17] X. Fang, et al.: “Linearity-enhanced Doherty power amplifier using output combining network with predefined AM-PM characteristics,” IEEE Trans. Microw. Theory Techn. 67 (2019) 195 (DOI: 10.1109/TMTT.2018.2870830).
[18] K. Bathich, et al.: “Frequency response analysis and bandwidth extension of the Doherty amplifier,” IEEE Trans. Microw. Theory Techn. 59 (2011) 934 (DOI: 10.1109/TMTT.2010.2098040).
[19] M.N.A. Abadi, et al.: “Doherty power amplifier with extended bandwidth improved linearizability under carrier-aggregated signal stimuli,” IEEE Microw. Wireless Compon. Lett. 26 (2016) 358 (DOI: 10.1109/LMWC.2016.2549281).
[20] W. Shi, et al.: “The influence of the output impedances of peaking power amplifier on broadband Doherty amplifiers,” IEEE Trans. Microw. Theory Techn. 65 (2017) 3002 (DOI: 10.1109/TMTT.2017.2673822).
[21] Z. Yang, et al.: “Bandwidth extension of Doherty power amplifier using complex combining load with noninfinite peaking impedance,” IEEE Trans. Microw. Theory Techn. 67 (2019) 765 (DOI: 10.1109/TMTT.2018.2884415).
[22] X. Chen, et al.: “A broadband Doherty power amplifier based on continuous-mode technology,” IEEE Trans. Microw. Theory Techn. 64 (2016) 4505 (DOI: 10.1109/TMTT.2016.2623705).
[23] C. Huang, et al.: “Design of broadband modified class-J Doherty power amplifier with specific second harmonic terminations,” IEEE Access 6 (2018) 2531 (DOI: 10.1109/ACCESS.2017.2784094).
[24] J. Kwon, et al.: “Broadband Doherty power amplifier based on asymmetric load matching networks,” IEEE Trans. Circuit Syst. II, Exp. Briefs 62 (2015) 533 (DOI: 10.1109/TCSII.2015.2407197).
[25] Y. Li, et al.: “Two-port network theory-based designed method for broadband class J Doherty amplifiers,” IEEE Access 7 (2019) 51028 (DOI: 10.1109/ACCESS.2019.2911891).

Table I. Comparison between current and previous work

| Ref  | Frequency (GHz) | Fractional Bandwidth (%) | Pout (dBm) | Saturated DE (%) | 6dB OBO DE (%) |
|------|----------------|--------------------------|------------|-----------------|---------------|
| [19] | 1.72–2.27      | 27.5                     | 42.5       | 58–72           | 48–55         |
| [23] | 3.3–3.75       | 12.7                     | 40–48.8    | 58–71           | 48–60         |
| [24] | 0.75–3.95      | 23.5                     | 48–48.8    | 55.4–64.7       | 51–63.8       |
| [25] | 2–5.43         | 45.7                     | 38.5–53.2  | 48–41           | 40–45         |

This work 1.6–2.1 27 43.2–44.5 48.1–72.1 48.4–63.5

Fig. 16 The ACPR, average DE and average Pout versus frequency

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[26] S.C. Cripps, et al.: “On the continuity of high efficiency modes in linear RF power amplifiers,” IEEE Microw. Wireless Compon. Lett. 19 (2009) 665 (DOI: 10.1109/LMWC.2009.2029754).
[27] V. Carrubba, et al.: “The continuous class-F mode power amplifier,” 40th Eur. Microw. Conf. (2010) 1674.
[28] N. Tuffy, et al.: “A simplified broadband design methodology for linearized high-efficiency continuous class-F power amplifiers,” IEEE Trans. Microw. Theory Techn. 60 (2012) 1952 (DOI: 10.1109/TMTT.2012.2187534).
[29] V. Carrubba, et al.: “Exploring the design space for broadband pas using the novel “continuous inverse class-F mode””, 41st Eur. Microw. Conf. (2011) 333 (DOI: 10.23919/EuMC.2011.6101840).
[30] M. Yang: “Highly efficient broadband continuous inverse class-F power amplifier design using modified elliptic low-pass filtering matching network,” IEEE Trans. Microw. Theory Techn. 64 (2016) 1515 (DOI: 10.1109/TMTT.2016.2544318).